A new & widely applicable bedform tracking tool

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List of symbols

A	Amount of data points per average bedform length
C	Filter span constant
d	Distance between two subsequent data points
k	Wave number
L_{av}	Average bedform length
L_c	Bedform length between two subsequent crests
L_{downcr}	Bedform length between two subsequent downcrossings
L_l	Length of the lee side of a bedform
L_p	Peak bedform length
L_s	Length of the stoss side of a bedform
L_t	Bedform length between two subsequent troughs
L_{upcr}	Bedform length between two subsequent upcrossings
m	Spectral moment
P_0	Trend line span
P	Filter span
S_{lee}	Steepness of the lee side of a bedform
Δ_l	Height of the lee side of a bedform
Δ_s	Height of the stoss side of a bedform
η_c	Crest elevation
η_t	Trough elevation
σ	Standard deviation

1 Introduction

Bedforms such as river dunes or marine sand waves are rhythmic bed features which develop by the interaction of water flow and sediment transport. Sometimes, river dunes are simply schematized as a train of regular triangles and sand waves are schematized as a sinusoidal wave train. However, measured bed elevation profiles show that bedforms are far from regular. Bedforms can be highly irregular in size, shape and spacing. To study the variability of geometric properties of measured bedforms, a method is needed that determines the locations of the crests and troughs in a measured bed elevation profile and then determines the geometric properties of individual bedforms. This document presents a method (a bedform tracking tool) to locate bedforms and determine their geometric properties. In this report we use the term 'bedform dimensions' to indicate the geometric properties of bedforms (such as bedform height, bedform length, trough elevation, crest elevation).

Problem description

A considerable amount of methods or numerical codes exists (e.g. Wilbers, 2004; Blom *et al.*, 2003; Leclair, 2002; Knaapen, 2005) to determine bedform characteristics from laboratory or field data. We expect that each method or code results in (slightly) other bedform characteristics. In order to compare bedform characteristics determined from various data sets correctly, all data sets have to be processed using the same method or code. Such an objective method that is applicable to both flume and field data (river and marine data) is not available.

Aim of report

The aim of this report is to present a method to determine the main bedform characteristics from measured bed elevation profiles as objectively as possible. The method is applicable to both field and flume measurements.

Outline

In Section 2 we give a short literature overview to discuss difficulties in determining geometric properties of bedforms. Section 3 describes the developed bedform tracking tool. Section 4 gives some first results of the bedform tracking tool. We end with conclusions and recommendations.

2 Existing bedform tracking methods

In this section, methods to determine bedform characteristics from a bed elevation profile (BEP) are described. The aim of the authors is not to give a complete overview of all existing methods; this literature review is meant to bring up difficulties that have to be dealt with when determining bedform characteristics from measured BEPs. In section 2.1 we describe methods to find the locations of crests and troughs. Section 2.2 treats other decisions that have to be made for determining bedform characteristics.

2.1 Selection of the locations of crests and troughs

Three possibilities exist to find crests and troughs in a measured BEP. Crest and trough locations are used to determine bedform dimensions. Possibilities are:

- to select crests and troughs manually;
- to find local extremes and select bedform heights and bedform lengths by introducing threshold values;
- to find troughs and crests between zero crossings.

In the following, we will discuss these possibilities.

Manual selection of crests and troughs

Blom *et al.* (2003) manually selected crests and troughs in measured BEPs using a Matlab code that remembers the set of selected crests and troughs. This is quite a quick method if there are not too many BEPs and if the bedforms are quite regular. However, as manual selection brings along subjective decisions, this method is not to be preferred. Moreover, we need a method or code that enables us to analyze many data sets, and, clearly manual selection is not suited for this task.

Selection of local extremes and definition of threshold values

Bakker (1982) developed a numerical code, DULOC (Dune LOCation), that determines the dimensions of bedforms on the basis of an analysis of local maxima and minima in a measured BEP. Bedform lengths and bedform heights were determined from the local maxima and minima. In DULOC, a threshold value for bedform height is used to overcome that small ripples are considered as bedforms.

Leclair (2002) measured and analyzed BEPs of laboratory flume experiments. She wrote a numerical code to determine the bedform dimensions, and also used threshold values for bedform height and bedform length. She adapted the definition for dunes as suggested by Allen (1984), since Leclair found Allen's definition too restrictive. Allen (1984) defined dunes as bedforms longer than 0.6 m and higher than 0.04 m. Gabel (1993) used Allen's definition for her field data. Leclair was able to track individual migrating dunes in successive BEPs. She also characterized bedforms with a height larger than 0.01 m and a length smaller than 0.6 m as dunes, as long as they reached a length of at least 0.6 m in one of the BEPs. The numerical code of Leclair cannot be used if the time gap between measured BEPs is so large that individual dunes cannot be tracked in successive BEPs anymore.

A disadvantage of using threshold values is that the value is chosen subjectively. A researcher chooses a threshold value based on the specific data set, while another researcher would choose another value for the same data set. Another disadvantage is that each data set may need other threshold values. For instance, Allen's definition may not be applicable to the data set on river dunes in the Paraná River in Argentina presented in Parsons *et al.* (2005). The height of dunes varied between 1.2 m and 2.5 m, while dune lengths varied between 45 m and 85 m. Superimposed bedforms reached a maximum of about 0.3 m in height and about 10 m in length (Parsons *et al.*, 2005). If the main interest is on the geometric properties of dunes, the threshold values have to be chosen such, that superimposed bedforms are not included in the analysis. The threshold values should be that dunes are, at least, higher than 0.3 m and longer than 10 m.

Selection of crests and troughs between zero crossings

Crests and troughs can be found by first selecting zero upcrossings and zero downcrossings of a BEP. Then, a crest is located between a zero upcrossing and a zero downcrossing, and a trough is located between a zero downcrossing and a zero upcrossing. A consequence of this method is that a small bedform that does not cross the X axis, will not be characterized as bedform. Another consequence is that a trough always is located below the zero line, and a crest above the zero line.

The chosen method to determine bedform dimensions from BEPs will influence the outcome. We illustrate this by plotting the probability density function (PDF) of bedform heights for one of the experiments of Blom *et al.* (2003). A sudden transition in the PDF may occur, if bedforms with a height below a certain threshold value are not considered as dunes. The PDF will not show such an abrupt step, if a dune is defined as the bedform between two subsequent upcrossings of the mean level. Figure 1a shows the PDF of dune heights when Allen's threshold value for dune height of 4 cm is used, whereas Figure 1b shows the PDF for the same experiment, but now a dune definition is used wherein a dune is defined as the bedform between two subsequent upcrossings. Clearly the shape of the PDF is influenced by the method to determine dune dimensions.

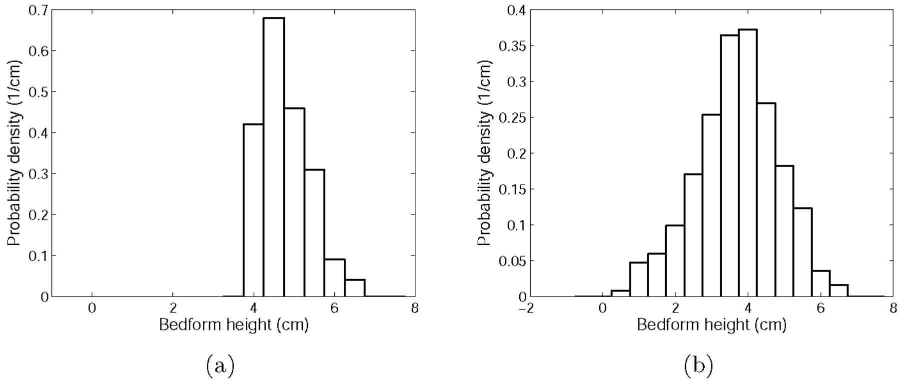


Figure 1: The chosen method to determine bedform dimensions influences the bedform dimensions. (a) A threshold value of 4 cm for bedform height is used. (b) Dunes are defined as bedforms between two subsequent upcrossings. The Figures present data of experiment T5 of Blom *et al.* (2003).

2.2 Choices that have to be made to define bedform dimensions

Besides the decision what method is used to determine bedform dimensions from a BEP, other choices have to be made. We will clarify the following choices.

- How do we determine the trend line of the bed elevation profile?
- Do we need to use a filter to eliminate smaller scale ripples and/or larger scale alternating bars?
- How do we define bedform dimensions?

Trend line

Subtraction of a trend line from the measured BEP, i.e. detrending, is needed in order to be able to study the fluctuations of bed elevations around a horizontal reference level. Nordin (1971) used a linear trend line to detrend his data. Mahmood & Ahmadi-Karvigh (1976) fitted a polynomial through the data and subtracted it from the data. Wesseling & Wilbers (2000) and Knaapen & Hulscher (2002) used a moving average technique for detrending the BEP. What type of trend line a researcher applies, is chosen by visual inspection of the data.

Filter to eliminate wave lengths

Smaller scale ripples and larger scale alternate bars can be excluded with the use of a filtering technique. For Missouri River data, Annambhotla *et al.* (1972) filtered out large-scale effects using a high pass filter. Mahmood &

Ahmadi-Karvigh (1976) filtered out frequencies lying outside the range of interest using a high pass filter, a single band pass filter and a band pass filter. A low pass filter is a filter that passes low frequencies but attenuates (or reduces) frequencies higher than the cutoff frequency. A high pass filter is the opposite, and a bandpass filter is a combination of a high pass and a low pass. Disadvantage of a filter technique is that the choice for the cutoff frequency is a subjective choice.

Definition of bedform dimensions

Bedform dimensions can be defined in various ways. Bedform length can be defined as the distance between two successive mean bed level upcrossings (L_{upcr} in Figure 2). A mean bed level upcrossing is defined as the point where the upward going BEP crosses the mean bed level. Bedform length can also be defined as the distance between two successive mean bed level downcrossings (L_{downcr}), the distance between two successive crests (L_c), or the distance between two successive troughs (L_t). Bedform height can be defined as the distance between a trough and its subsequent crest (Δ_s) or between a crest and its subsequent trough (Δ_l) (Figure 2). Most researchers (e.g. Leclair, 2002; Blom *et al.*, 2003) use the vertical distance between a crest and its downstream trough as a definition of bedform height. The definitions of bedform length and bedform height by Wesseling & Wilbers (2000) and Wilbers (2001) are not often used. They define dune length as the length of a line connecting two subsequent troughs. They define bedform height as the shortest distance between a crest and the line between two troughs (Figure 3). A disadvantage of the method by Wesseling & Wilbers (2000) and Wilbers (2001) is that two troughs are needed to be able to determine the height of a bedform. Especially in the case of short BEPs with lengths of only a few meters, this can be disadvantageous, since it is desirable to consider as many bedforms as possible.

Decisions on the type of trend line, on the definitions that are used for bedform dimensions, on whether to use threshold values, and whether to filter the data may influence the resulting bedform characteristics. These decisions are usually made subjectively on the basis of the whole bed configuration (Crickmore, 1970). In order to compare various sets of experiments of different researchers with each other correctly, it is necessary for all data sets (a) to use the same method for finding crests and troughs and (b) to use the same definitions for bedform dimensions. Therefore, it is generally not desirable to compare bedform data of different researchers if the original bed elevation profiles are lacking (Crickmore, 1970).

2.3 Available software packages

Wesseling & Wilbers (2000) and Wilbers (2001) developed the DT2D software application to analyze measurements of the Waal River. Large disadvantage of the application is that it seems only suitable for Waal River

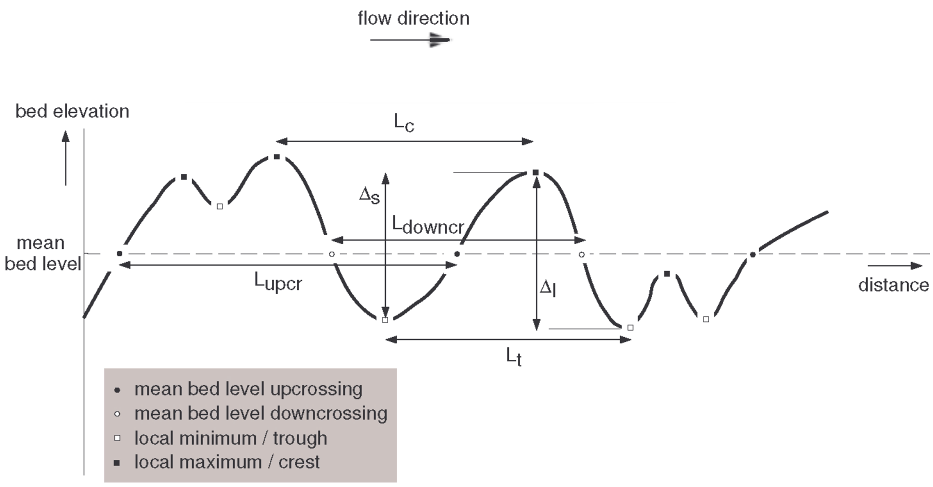


Figure 2: Possible definitions for bedform length and bedform height. See the text for an explanation of the symbols.

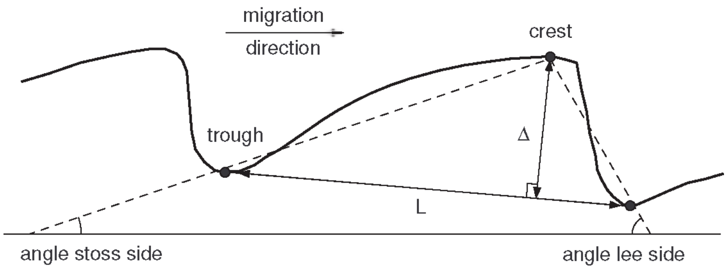


Figure 3: Definitions of bedform length and bedform height by Wesseling & Wilbers (2000).

measurements. We inserted some BEPs of flume experiments to test the application. The application was not able to select crests and troughs correctly, as probably the code always tries to find secondary bedforms, even if these are not present.

Another software application is Bedformer 2.1.1 developed by Clunie (no documentation or reference available). Bedformer is free to download the application from Clunie's website [1]. The application gives undesirable results at the boundaries of a BEP. The first and/or last measured data points are characterized as crest or trough if these points are a local maximum or minimum. Furthermore, Bedformer was not able to select crests and troughs in a BEP of the Waal River, probably because of the length of the domain or the presence of secondary bedforms in some BEPs.

[1] http://www.engineers.auckland.ac.nz/~tclu001/software.htm, downloaded October 2006

3 Method to determine bedform characteristics

We developed a bedform tracking tool by writing a numerical code in Matlab (version 7 R14). The tool automatically selects crest and trough locations in measured BEPs and determines bedform dimensions. The bedform tracking tool (BBT) is written such that as few as possible subjective choices have to be made and such that the tool is applicable to all kinds of measurements (field and flume). We describe the procedure to determine bedform characteristics from a BEP in section 3.1. Section 3.2 explains how the BBT treats BEPs with secondary bedforms. In section 3.3 the chosen procedure is evaluated.

3.1 Procedure of the bedform tracking tool

First, we shortly list the steps in the procedure. After that, each of the steps is explained in closer detail.

1. For each BEP we find outliers and replace them. The data without outliers is saved.

2. For each BEP we determine the trend line. For flume experiments under uniform conditions (i.e. there are no spatial variations), this trend line is a linear fit to the measured bed elevations. For field measurements, the trend line is determined using a weighted moving average procedure.

3. We detrend the BEP using the equilibrium trend line. The new BEP now fluctuates around the zero line.

4. We apply a weighted moving average filter. This yields a filtered BEP which is used for determining zero up- and downcrossings only.

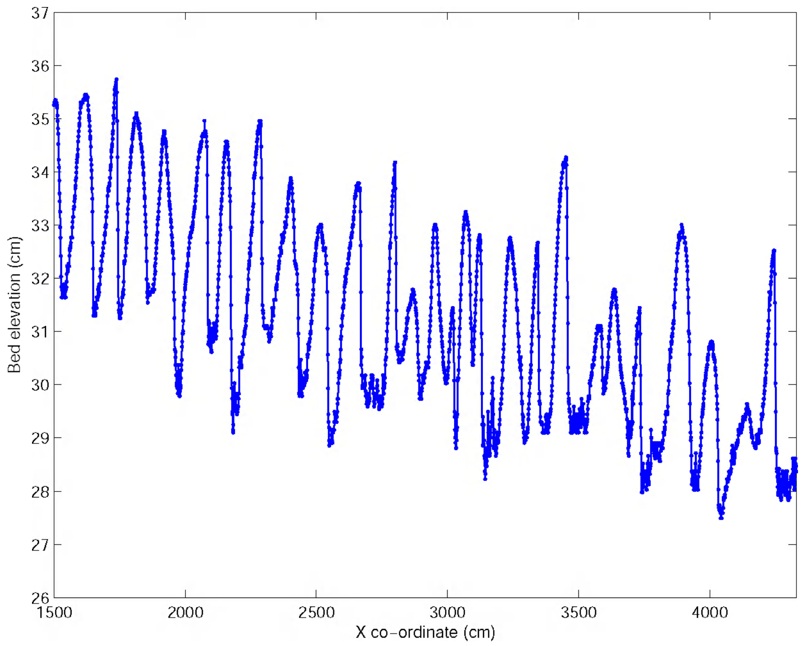
5. We determine zero upcrossings and zero downcrossings of the filtered BEP.

6. We determine crests and troughs. A crest is located between a zero up- and zero downcrossing. A trough is located between a zero down- and zero upcrossing.

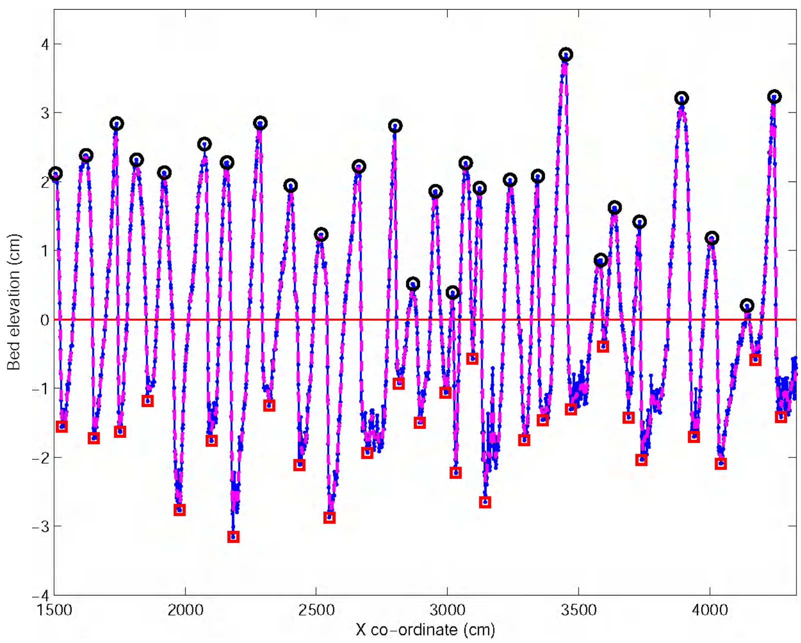
7. At the boundaries of a BEP, crests and/or troughs may be present which are not recognized as such by the code, as they are not surrounded by two zero crossings. We find these crests and troughs.

8. We determine and save bedform characteristics (crest locations, trough locations, bedform heights, bedform lengths, steepness of the lee side).

Figure 4 gives a graphical representation of the result of the procedure (the steps 2 through 7).



(a)



(b)

Figure 4: Example of the procedure (steps 2 – 7). a) The original BEP as measured in the laboratory flume. b) The detrended BEP. The dashed line is the filtered BEP which is used for determining the zero crossings. Squares indicate the troughs and circles indicate the crests. The example shows a BEP of experiment T5 of Blom *et al.* (2003).

3.1.1 Step 1. Removing outliers

When a BEP consists of outliers (e.g. measuring errors), it may happen that maxima or minima are incorrectly specified as crests or troughs, respectively (Figure 5). Therefore, we remove outliers before we start determining crests and troughs.

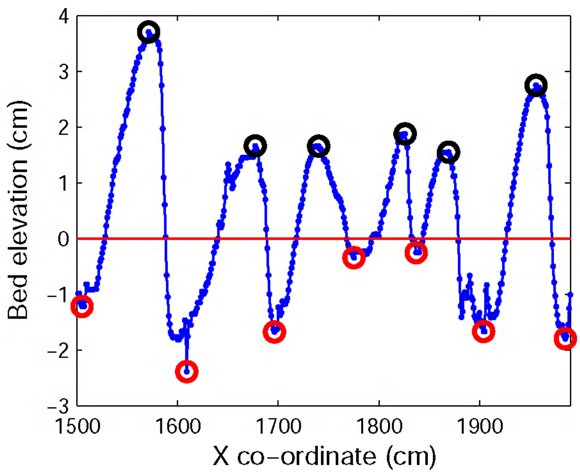


Figure 5: A minimum (outlier) is incorrectly specified as a trough. Part of a BEP of experiment T5 of Blom *et al.* (2003) is shown.

The absolute vertical distances dz between all subsequent measured points are computed. The mean value of all vertical distances, dz_m, which is a measure for vertical deviations, is then used to find outliers. An outlier is defined as a point that deviates more than $\pm 5dz_m$ with its previous point and $\mp 5dz_m$ with its next point. The user is asked whether he/she wants to replace the point(s) with point(s) determined with a linear interpolation or wants to keep the point(s). Then, we ask the user whether he/she wants to replace other points that the code did not recognize as outliers. The user can manually select outliers. Then the code saves the corrected data.

3.1.2 Step 2. Determining equilibrium trend line

We ask the user whether he/she prefers a) a linear trend line or b) a weighted moving average trend line.

a) In a laboratory flume, an experiment is often run until the flow and transport has reached an equilibrium stage. Several BEPs may be measured during equilibrium conditions. Experiment T5 of Blom *et al.* (2003), for example, consists of 20 BEPs that were measured in the equilibrium state. We consider these 20 BEPs as statistically homogeneous. We verified if the BEPs are indeed statistically homogeneous using a spatial scaling technique (Barabási & Stanley, 1995; Jerolmack

& Mohrig, 2005). This is not included in the BTT. The trend lines of these individual BEPs can deviate from each other, because a BEP can consist of incomplete bedforms or only a few bedforms. Especially in short flumes the trend lines of the individual BEPs can fluctuate considerably. Therefore the equilibrium trend line is determined by taking the average trend line of the individual BEPs.

b) For field measurements, a linear trend line may not be suitable as the mean river bed is usually a fluctuating line rather than a linear line. The user can choose to apply a weighted moving average filter to determine the trend line. A weighted moving average filter smooths data by replacing each data point with the weighted average of the neighboring data points defined within a given span. The span defines the amount of neighboring points that are used to take the weighted average. The span must be odd to prevent a phase shift.

   We determine the trend line span (P_0) as follows. For each trend line span value P_0 ranging from 3 through the amount of data points, we determine a peak bedform length using a spectral density function. We plot the peak bedform length against the trend line span. Such a plot gives information on the dominant bedform lengths that are present in the BEP. The user then chooses the bedform length that he/she is interested in. The code will use the trend line span that corresponds to this bedform length to determine the trend line. In Appendix A we present in more detail how we determine the span as objectively as possible.

3.1.3 Step 3. Detrending the bed elevation profile

We detrend the BEP by subtracting the trend line from the original BEP. The detrended BEP fluctuates around the zero line.

3.1.4 Step 4. Weighted moving average filter

We determine a filtered BEP using a weighted moving average technique in order to determine zero crossings. We use a Hann filter to determine the set of weights. The Hann filter is a symmetric filter with weights decreasing from the central weight. In this way not every small disturbance that crosses the zero line is specified as a zero crossing (Figure 6). An important choice is the span that is used in creating the filtered BEP. A small filter span results in a signal that is almost equal to the original BEP. In that case crossings with the zero line will wrongly be interpreted as up- and downcrossings of a bedform. On the other hand, a larger filter span will filter away the bedforms. The span depends both on the length of the bedforms of interest in the BEP and on the distance between two subsequent data points. We take the following steps to determine the span:

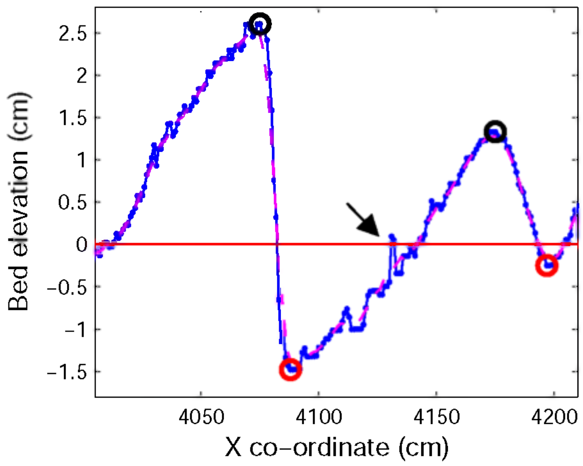


Figure 6: A filter is needed to prevent that a small disturbance that crosses the zero line is considered to be a bedform. The dashed line indicates the filter. Part of a BEP of experiment T5 of Blom *et al.* (2003) is shown.

a) We plot a spectral density function of the BEP. The spectral density function gives the distribution of power per wave number k. Wave number is defined as $k = 1/L$, where L is the bedform length. The total area under the spectral density function is equal to the variance of the BEP.

b) We compute the mean bedform length L_{av} from the spectral moments of the spectral density function m_0 and m_1:

$$L_{av} = m_0/m_1 \quad [\mathrm{m}]$$

Here L_{av} is the wave length that belongs to the wave number k_{av}. The wave number k_{av} $(= m_1/m_0)$ can be regarded as the center of gravity of the spectral density function.

c) We compute the amount of data points per bedform length L_{av}. Let A denote the amount of data points per bedform length L_{av} and d the horizontal distance between two subsequent data points. Then:

$$A = L_{av}/d + 1 \quad [-]$$

d) We compute the filter span, P:

$$P = CA \quad [-] \quad \text{with } C = 1/6 \quad \text{(a constant)}$$

e) As the filter span needs to be an odd integer, P is rounded towards the nearest odd integer.

We call C the 'filter span constant'. We apply a weighted moving average filter with a span $P = CA$, in which $C = 1/6$. $P = 1/6A$ means that the span is equal to one sixth of the length of the significant bedform. The larger the filter span constant, the more the filtered BEP deviates from the original BEP. We illustrate this in Figure 7 and Figure 8. Using a filter span constant much smaller than 1, for instance $C = 1/40$, small features that cross the zero line will be considered in the analysis as the original BEP and the filtered BEP are almost equal. Figure 7 shows this for $C = 1/40$. Using a filter span constant of order 1/2 or 3/4, the filtered BEP will deviate from the original BEP. As a result, the up- and downcrossings are not correctly selected. Figure 8 shows this for $C = 3/4$. Up- and downcrossings of the filtered BEP do not correspond to up- and downcrossings of the original BEP, so that not all crests and troughs are tracked. As a result, bedform length – defined as the horizontal distance between two subsequent crests – is larger than should be (Figure 8). We have chosen a filter span constant of $C = 1/6$. In Appendix B we discuss the choice of the value $C = 1/6$.

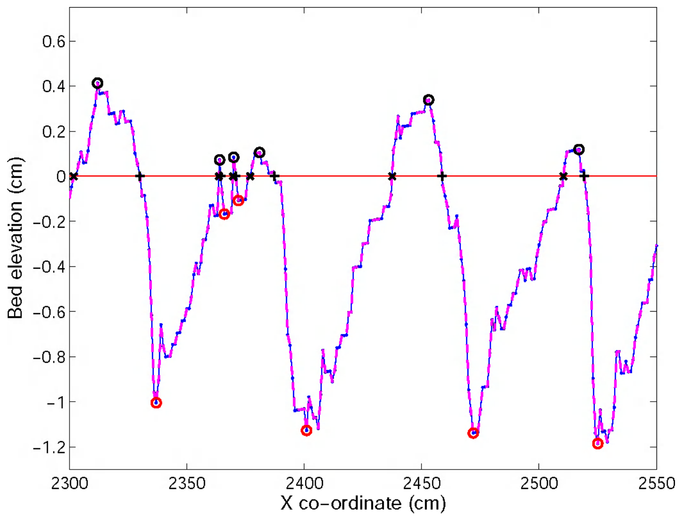


Figure 7: The influence of the span value C (here $C = 1/40$). The filtered BEP is indicated with the dashed line. Up- and downcrossings are indicated with x and +, respectively. Crests and troughs, indicated with circles, are located between the crossings. Small features that cross the zero line are considered in the analysis. Part of a BEP of experiment A1 of Blom *et al.* (2003) is shown.

3.1.5 Step 5. Determining zero crossings

We determine zero upcrossings and zero downcrossings of the filtered BEP. A zero upcrossing is located where the filtered BEP crosses the zero line in upward direction. Likewise, a zero downcrossing is located where the filtered BEP crosses the zero line in downward direction.

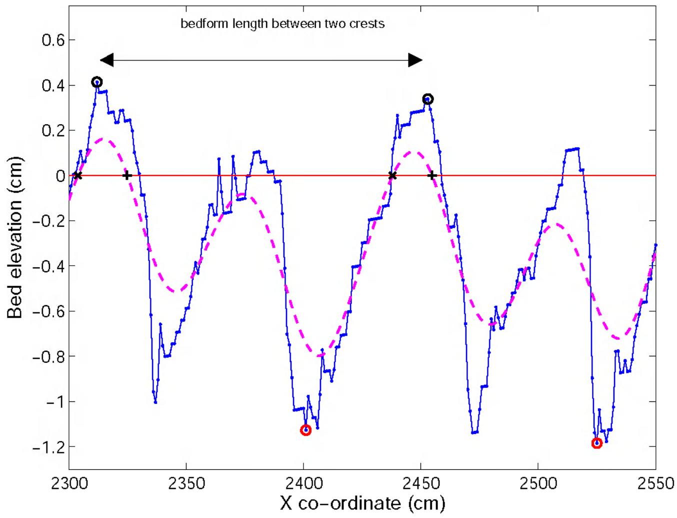


Figure 8: The influence of the span value C (here $C = 3/4$). The filtered BEP is indicated with the dashed line. Up- and downcrossings are indicated with x and +, respectively. Crests and troughs, indicated with circles, are located between the crossings. As up- and downcrossings of the filtered BEP do not correspond to up- and downcrossings of the original BEP, bedform lengths are too large. Part of a BEP of experiment A1 of Blom *et al.* (2003) is shown.

3.1.6 Step 6. Determining crests and troughs

A crest is located between a zero upcrossing and zero downcrossing. We first determine the location of the maximum value of the filtered BEP between an up- and downcrossing. Then, the crest is located at the maximum value of the original BEP within the filter span (P) of this maximum value of the filtered BEP. Likewise, we determine the location of the minimum value of the filtered BEP between a down- and upcrossing. The trough is located at the minimum value of the original BEP within the span of the minimum value of the filtered BEP. Note that we determine the crest and trough locations from the original detrended BEP. We only use the filtered BEP to find the rough locations of the crests and troughs. If we would just take the highest or lowest data point between two zero crossings in the original detrended BEP as the crest or trough location respectively, a local disturbance could wrongly be selected as crest or trough (Figure 9).

3.1.7 Step 7. Crests and troughs at the boundaries of the bed elevation profile

Crests and troughs are found between two crossings. At the start and end of a BEP a crest or trough may be present that is not characterized as such in case the BEP does not cross the zero line. Especially in short BEPs it is desirable to incorporate as many crests and troughs as possible

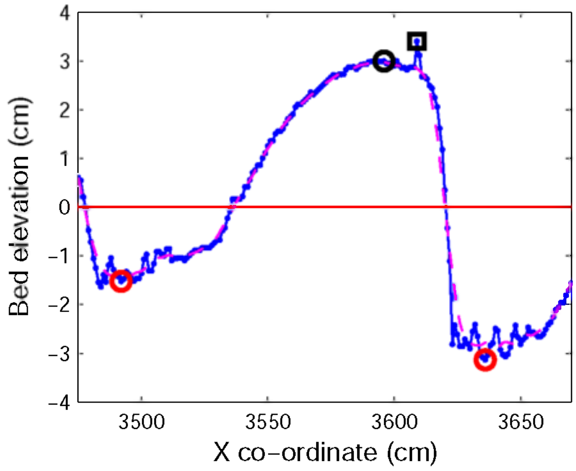


Figure 9: A crest is defined as the highest point of the original detrended BEP within the span of the maximum value of the filtered BEP between an upcrossing and a subsequent downcrossing. If we would just take the highest value of the original detrended BEP as the crest location, a small disturbance would be selected as the crest (indicated with a square). Part of a BEP of experiment T5 of Blom *et al.* (2003) is shown.

in the analysis. Figure 10 shows that the minimum close to $X \approx 4300$ cm clearly is a trough, but it is not characterized as such as it is not located between a downcrossing and an upcrossing. Therefore, we look for crests and/or troughs at the boundaries of the BEP. There are four possibilities (Figure 11):

a) a crest is located before the first downcrossing;

b) a crest is located after the last upcrossing;

c) a trough is located before the first upcrossing;

d) a trough is located after the last downcrossing.

We can only characterize a maximum or minimum as a crest or trough respectively, if there are enough data points measured before (possibilities a and c) or after (possibilities b or d) the extreme values. We only specify an extreme value as crest or trough if the amount of data points before or after the extreme value is larger than or equal to half the filter span, $0.5P$ (see shaded areas in Figure 11).

3.1.8 Step 8. Determining bedform characteristics

In our research, we are not only interested in the mean values, but also in the stochastic properties of bedform dimensions. Therefore, all individual bedform heights and lengths are saved in arrays.

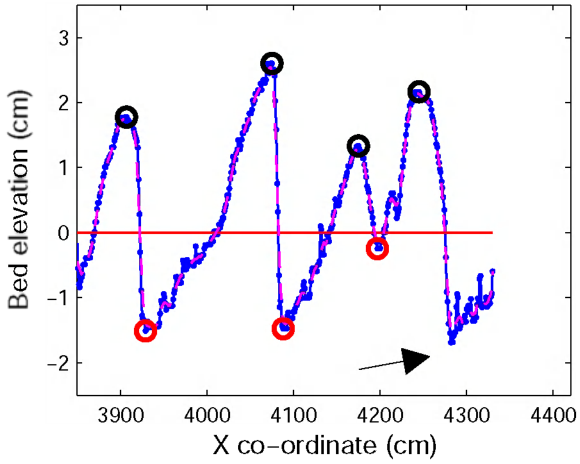


Figure 10: A trough is located at the boundary of the BEP. This trough is not recognized as such, as it is not surrounded by two crossings. Part of a BEP of experiment T5 of Blom *et al.* (2003) is shown.

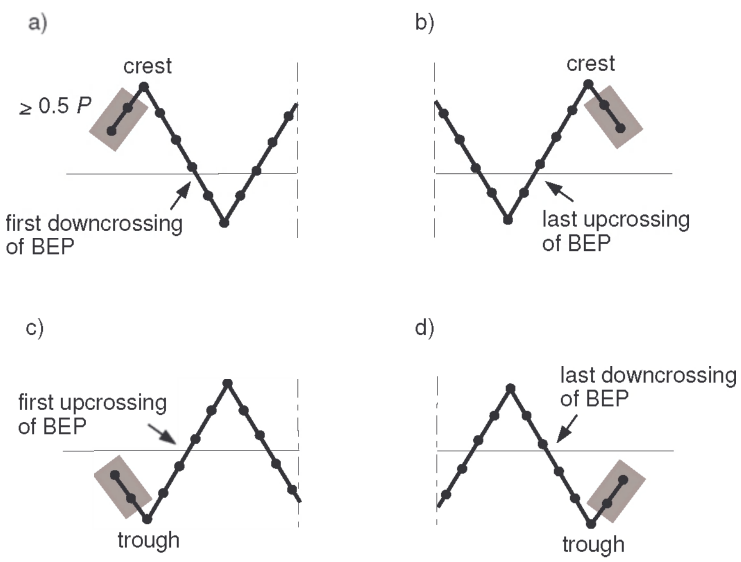


Figure 11: Sketches of the four possibilities for extreme values at the boundaries of a BEP. If the amount of data points in the shaded areas is larger than or equal to $0.5P$, the maximum or minimum is selected as crest or trough respectively.

The following bedform characteristics are determined in the detrended BEP and saved (Figure 12):

Symbol	Bedform dimension		Explanation
η_c	Crest elevation	-	Vertical distance from crest to equilibrium trend line
η_t	Trough elevation	-	Vertical distance from trough to equilibrium trend line
Δ_s	Height of stoss side	-	Vertical distance between crest and upstream trough
Δ_l	Height of lee side	-	Vertical distance between crest and downstream trough
L_s	Length of stoss side	-	Horizontal distance between crest and upstream trough
L_l	Length of lee side	-	Horizontal distance between crest and downstream trough
L_c	Bedform length between crests	-	Horizontal distance between two subsequent crests
L_t	Bedform length between troughs	-	Horizontal distance between two subsequent troughs
L_{upcr}	Bedform length between upcrossings	-	Horizontal distance between two subsequent upcrossings
L_{downcr}	Bedform length between downcrossings	-	Horizontal distance between two subsequent downcrossings
S_{lee}	Steepness lee side of bedform	-	Vertical distance divided by horizontal distance of a part of the lee side

For determination of the steepness of the lee side of a bedform, we do not consider the whole lee side region between crest and its subsequent trough, but we exclude a distance of one sixth of the bedform height below the crest and a distance of one sixth of the bedform height above the trough. The rectangle in Figure 12 illustrates which part of the lee side we use to determine the steepness of the lee side of the bedform. We fit a linear line through the data points within this part of the lee side to determine the steepness. We exclude the lee side slopes which are determined from a falling, rising and falling lee side (dashed line in Figure 13).
Individual bedform dimensions are saved. Furthermore, mean values and standard deviation of bedform characteristics are determined and saved. The equilibrium trend line is also saved.

3.1.9 Built-in checks

To check whether the output of our code is correct, we built in some internal checks. We check if both the upcrossings and downcrossings and the troughs

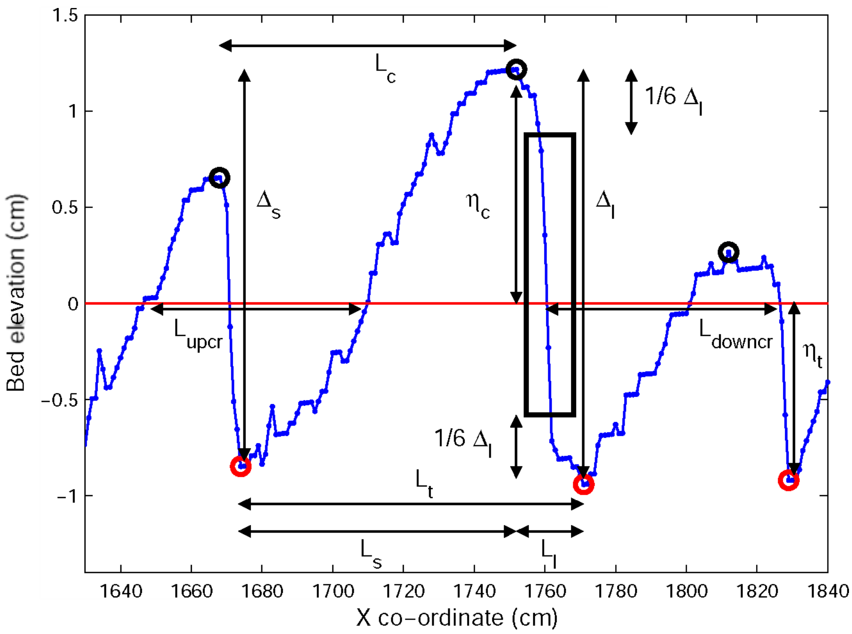


Figure 12: Definitions of the determined bedform characteristics. See the text for an explanation of the symbols. The flow is from left to right. Part of a BEP of experiment A1 of Blom *et al.* (2003) is shown.

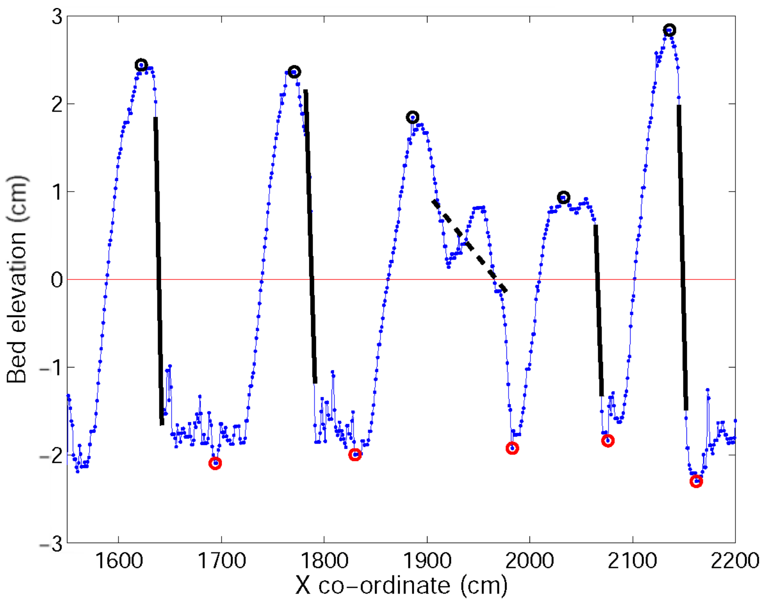


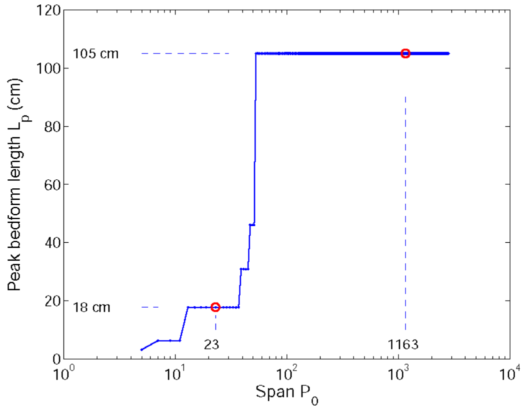
Figure 13: Determination of the steepness of the lee side. The linear lines indicate the slopes. The dashed slope is excluded from the analysis. Part of a BEP of experiment T5 of Blom *et al.* (2003) is shown.

and crests are found alternately. As a result of the chosen method for crest and trough tracking, crests are located above the zero line and troughs below the zero line. This is checked for all crests and troughs. Finally, each BEP – together with the selected crests and troughs – is plotted and screened visually.

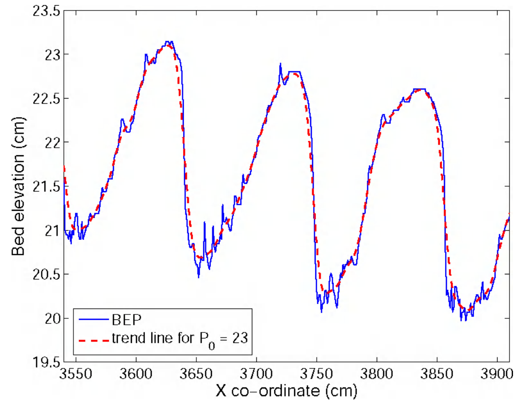
3.2 Secondary bedforms

River dunes and marine sand waves are often covered with smaller scale bedforms (ripples or megaripples). The BTT is able to determine bedform characteristics of more than one bedform type. In Section 3.1.2b) we show that – if the user chooses to use a weighted moving average trend line – the BTT determines the dominant bedform lengths that are present in the BEP. The dominant bedform lengths are determined by plotting the peak bedform length against the trend line span. The user has to select which bedform length he/she is interested in. It is possible to select more than one dominant bedform length. If more than one dominant bedform length is chosen, the code runs for each bedform length and saves the bedform characteristics for each bedform length separately.

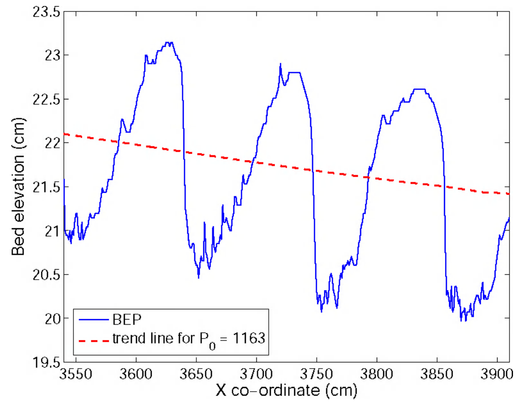
Figure 14 illustrates this for a BEP of one of the flume experiments of Blom *et al.* (2003) (this example is also used in Appendix A). Figure 14a shows the plot of the peak bedform length against trend line span. This graph shows that two dominant bedform lengths are present in the BEP, ripples and dunes. The code runs twice if the user specifies that he/she is interested in the bedform lengths of both order 18 cm and order 105 cm (Figure 14a). The first time, the code uses a trend line which is determined by using a trend line span of $P_0 = 23$ (Figure 14b). The code determines the bedform characteristics of the ripples. The second time, the code uses a trend line which is determined by using a trend line span of $P_0 = 1163$ (Figure 14c). The code determines the bedform characteristics of the dunes.



(a)



(b)



(c)

Figure 14: Illustration of the determination of dominant bedform lengths for a flume experiment. a) Peak bedform length against the trend line span. The horizontal parts (sills) indicate the dominant bedform lengths. b) Original BEP together with the trend line (dashed) determined with a span of $P_0 = 23$. c) Original BEP together with the trend line (dashed) determined with a span of $P_0 = 1163$.

3.3 Evaluation of the procedure

Consequences of the zero crossing method

We have chosen to apply a zero crossing method for the determination of crests and troughs. This choice brings along some consequences.

- Bedform A in Figure 15 is not characterized as a bedform since the crest is not located above the zero line. This has consequences for the bedform dimensions, mainly for the bedform length. Mean bedform length would be smaller if bedforms such as A would be characterized as bedforms.

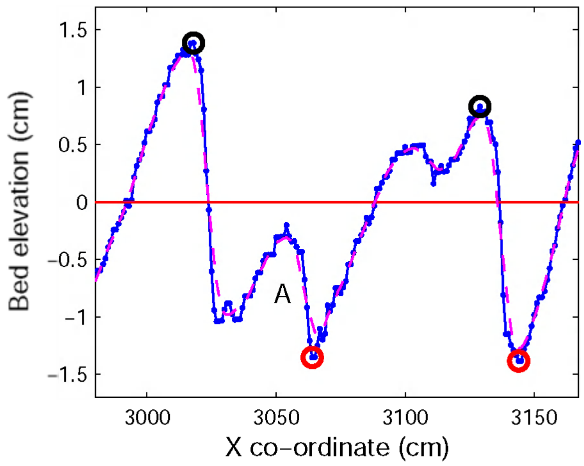


Figure 15: Bedform A is not characterized as a bedform since it does not cross the zero line. Part of a BEP of experiment A1 of Blom *et al.* (2003) is shown.

- In Figure 15, we show that sometimes small bedforms are not characterized as bedforms. However, sometimes a small bedform *is* characterized as a bedform, while it is in fact much smaller than, for instance, bedform A of Figure 15. This occurs in the neighborhood of the zero line (Figure 16).

- A characteristic of a moving average filter is that, due to averaging, the amplitude of a filtered signal is smaller than the amplitude of the original signal. As a result, a bedform may cross the zero line, whereas the filtered BEP does not. Then, this bedform is not characterized as such (Figure 17). Again this has consequences for the bedform length. How often this occurs depends on the filter span constant (C). The larger the filter span constant, the more often this occurs.

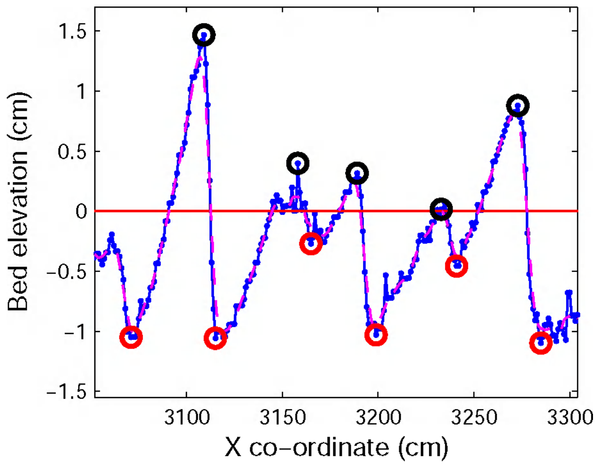


Figure 16: Small bedforms fluctuating around the zero line are characterized as bedforms. Part of a BEP of experiment A1 of Blom *et al.* (2003) is shown.

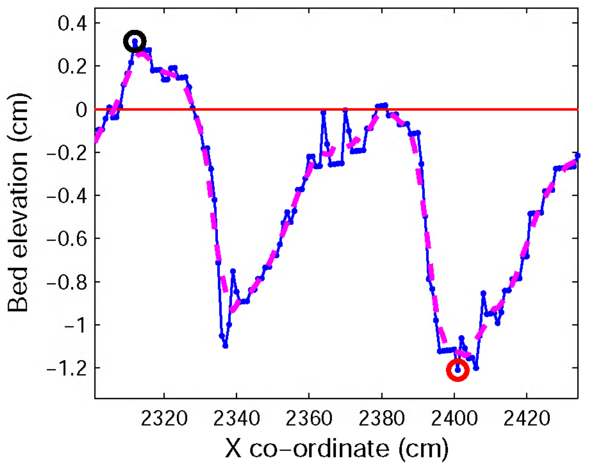


Figure 17: A bedform is not characterized as such, as the filtered BEP (dashed line) does not cross the zero line. Part of a BEP of experiment A1 of Blom *et al.* (2003) is shown.

Use of the weighted moving average trend line

The trend line span P_0 needed to determine the moving average trend line is determined by first plotting a graph of peak bedform length against span. With the help of this graph, the user can select the bedform length of his/her interest; the corresponding trend line span is then used to determine the trend line and detrend the data. Making this graph takes some computational time. It takes roughly 3 minutes to plot such a graph for a BEP of 3000 data points (on a Pentium 4 computer). We save the data that are needed to plot the graph, so that the plotting takes 3 minutes only once.

The ‘peak bedform length - trend line span’ graph shows one or more horizontal parts, the sills. Each sill corresponds to a dominant bedform length, as we explain in Appendix A. A BEP may be too long if a lot of sills are found in the ‘peak bedform length versus trend line span’ graph. A long BEP may consist of a lot of dominant bedform lengths. We determine the trend line span that corresponds to a sill by choosing the span value located at 0.4 times the length of the sill (just left of the center of the sill). The value of 0.4 is found by trial-and-error. In Figure 18a we schematize a BEP which consists of a linear trend and three sine waves with different amplitudes and lengths (we use the same example in Appendix A). The user can specify which bedform lengths he/she is interested in (10 cm, 100 cm, 700 cm in this example). The trend line that corresponds to bedform length of 700 cm should describe a linear line. The trend line that corresponds to a bedform length of 100 cm should describe – in this example of ideal sinusoids – a sine wave with wave length of 700 cm added to the linear line. If we choose as trend line span a value located at 0.4 times the length of the sill, we find trend lines that best agree with the ideal sinusoidal trend lines.

The code runs twice if the user selects 10 cm and 100 cm as bedform lengths of interest. Figure 18b shows the detrended BEP and the resulting crests and troughs which are found for the bedform length of 10 cm. Figure 18c shows the detrended BEP and the resulting crests and troughs which are found for the bedform length of 100 cm. From Figures 18b and 18c it can be seen that the moving average trend lines do not exactly describe sine waves; the amplitudes of the moving average trend lines are somewhat smaller than the amplitudes of the three sine waves that we used to schematize the original BEP. As a result, the crests and troughs of detrended BEPs do not lie on a straight horizontal line. This has consequences for the standard deviation of bedform height. There is a need to improve the BTT with respect to this aspect.

The method we present here to determine the fluctuating trend line has some disadvantages, as we described above. Also we realize that the method is somewhat laborious, since we first compute all trend lines and corresponding detrended BEPs to finally choose one of these trend lines. For now, it suits our goal, namely to determine trend lines for river data without the necessity to adjust the code for each data set.

Objectivity of the bedform tracking tool

The aim is to develop a BTT that is as objectively as possible in order to use it for various data sets. We have tried to avoid subjective decisions – such as values for threshold values – as much as possible. Nevertheless, the proposed method consists of four quantitative choices:

1) $\pm 5dz_m$ for the outlier selection,

2) the span value P_0 corresponding to a dominant bedform length to detrend the BEP in case a weighted moving average trend line is used,
3) the filter span constant $C = 1/6$ to determine the filter span P for the filtered BEP,
4) $0.5P$ for the selection of crests and troughs at the boundaries of the BEP.

We wrote the numerical code such, that it can be applied to each data set, without the necessity to tune the code to each data set. At the moment, we applied the code successfully to river data, marine sand wave data and flume data. It appeared that there was no need to change the subjective decisions.

If the BBT does not perform as expected, the user might have to adjust one of the subjective decisions. If the BTT does not select outliers while these are present, we suggest to decrease the value of 5. On the other hand, if the BTT selects data points as outliers, whereas these points are no outliers, we suggest to increase the value of 5.

The BTT plots the original BEP together with the trend line on the screen. If the trend line is not as expected, the value for the trend line span P_0 is probably wrongly determined. The user can manually specify a trend line span value.

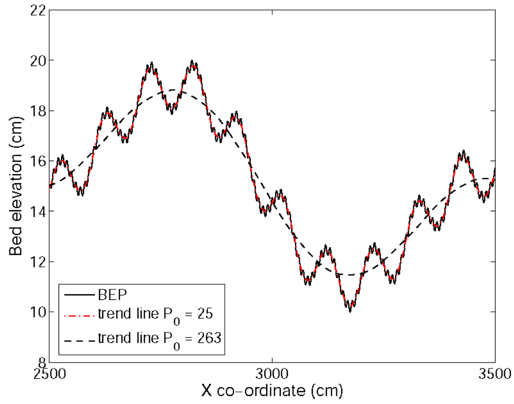
The filter span constant C has to be adjusted if the zero crossings are not found at the right locations. This can be seen immediately in the figure where the detrended BEP is plotted together with the filtered BEP and the resulting crests and troughs.

If, at the boundaries of a BEP, crests or troughs are wrongly selected, we suggest to replace the value of 0.5 by a larger value. This is an innocent adjustment; if the value is larger, the BTT will not find crests and/or troughs at the boundaries.

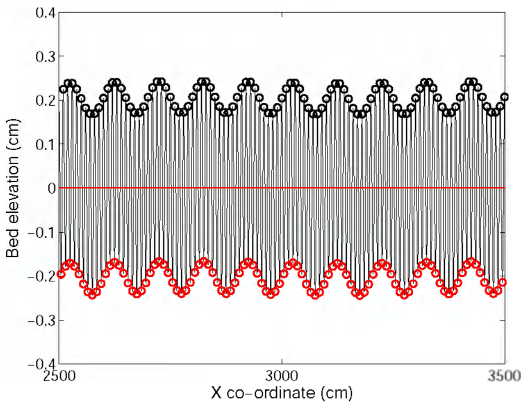
Limitations of the bedform tracking tool

The BTT can only be applied to data sets in which bed elevations are measured on a uniformly spaced grid ($d = \text{const}$).

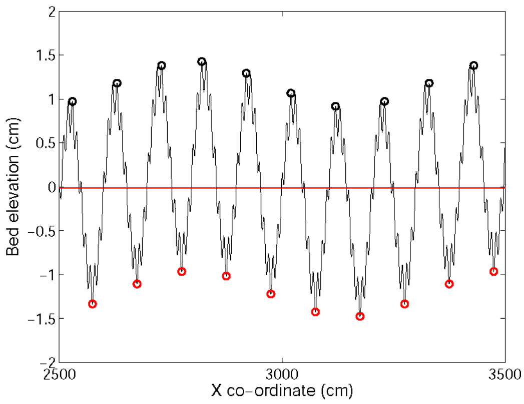
In the case of Barchan dunes or solitary bedforms (Figure 19) bedform length is sometimes defined as the horizontal distance between the stoss toe and lee toe, as Carling *et al.* (2000) sketched in their definition diagram (their Figure 5). The bedform length between stoss toe and lee toe is smaller than the horizontal distance between two crests. We do not determine the locations of the stoss toe and lee toe in the BTT.



(a)



(b)



(c)

Figure 18: BTT runs twice if the user specifies two bedform lengths of interest. a) The original BEP, schematized as three sine waves added to a linear trend. b) The detrended BEP determined by subtracting the moving average trend line (determined by using a span of 25) from the original BEP. c) The detrended BEP determined by subtracting the moving average trend line (determined by using a span of 263) from the original BEP.

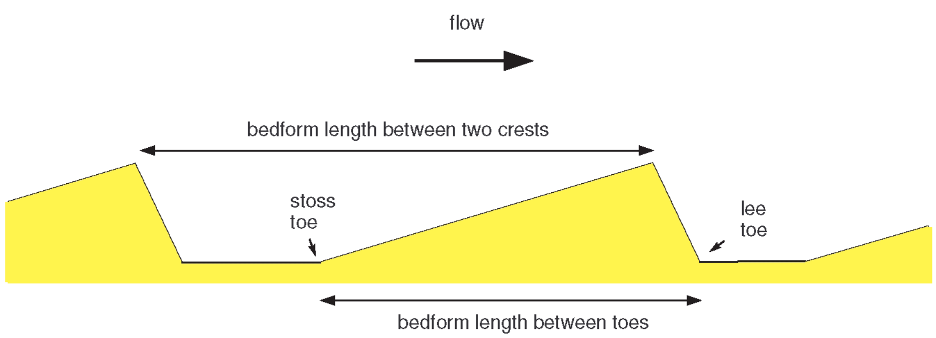


Figure 19: Bedform length defined as the distance between the stoss toe and lee toe in case of solitary bedforms is smaller than the bedform length defined as the distance between two crests.

4 Results of the bedform tracking tool

The BTT is used to analyze laboratory flume data of Blom *et al.* (2003), Leclair (2002), Driegen (1986), and Klaassen (1990). We have only selected data from the steady state situations. Table 1 shows some important characteristics of the experiments. Sets 1, 2, 3 and 7 were conducted using non-uniform sediment. Sets 4, 5 and 6 were conducted using uniform sediment. The original BEPs of all 58 experiments are available. Except for set 1, BEPs are measured in the center of the flume, and left and right of the center. BEPs of set 1 are only measured in the center. The BTT has been used to determine bedform characteristics from the original BEPs.

In section 3.1.8 we show that – in the BTT – bedform height is determined in two ways:

1) vertical distance from crest to upstream trough, Δ_s,

2) vertical distance from crest to downstream trough, Δ_l.

And bedform length is determined in four ways:

1) distance between crests, L_c,

2) distance between troughs, L_t,

3) distance between upcrossings, L_{upcr},

4) distance between downcrossings, L_{downcr}.

In the next section we compare mean bedform heights ($\overline{\Delta_s}$, $\overline{\Delta_l}$) and mean bedform lengths ($\overline{L_c}$, $\overline{L_t}$, $\overline{L_{upcr}}$, $\overline{L_{downcr}}$). We also compare standard deviations of bedform heights (σ_{Δ_s}, σ_{Δ_l}) and standard deviations of bedform lengths (σ_{L_c}, σ_{L_t}, $\sigma_{L_{upcr}}$ and $\sigma_{L_{downcr}}$).

For the comparisons we use the 58 experiments listed in Table 1. Bedform dimensions measured left and right of the center deviate slightly from the bedform dimensions in the center of the flume due to side wall effects. Therefore we distinguish between BEPs measured in the center, left of the center and right of the center. The figures below, in which the comparisons are visualized, consist of 164 data points. Each data point represents a BEP location for an experiment: 53 experiments times 3 BEP locations (center, left and right) + 5 experiments (BU9, BU14, BU21, A1, B1) times 1 BEP location (center) yields 164 data points.

4.1 Mean bedform height

Figure 20 shows a comparison between mean bedform height defined as the vertical distance from crest to downstream trough, $\overline{\Delta_l}$, and mean bedform height defined as the vertical distance from crest to upstream trough, $\overline{\Delta_s}$.

Table 1: Characteristics of laboratory flume experiments

Set	Exp.	L (m)	W (m)	h (m)	u (m/s)	D_{50} (mm)	$\overline{\Delta}$ (mm)
1	BU9	7.6	0.6	0.15	0.50	0.43	44.1
Leclair	BU14	7.6	0.6	0.15	0.60	0.43	56.9
(2002)	BU21	7.6	0.6	0.15	0.75	0.43	47.7
2	T5	50	1.5	0.245	0.69	1.3	37.0
Blom *et al.*	T7	50	1.5	0.354	0.79	1.3	52.5
(2003)	T9	50	1.5	0.260	0.70	1.3	49.2
	T10	50	1.5	0.193	0.59	1.3	18.5
3	A1	50	1.0	0.154	0.64	mix*	23.9
Blom *et al.*	A2	50	1.0	0.320	0.83	mix*	42.8
(2003)	B1	50	1.0	0.155	0.63	mix*	26.3
	B2	50	1.0	0.389	0.69	mix*	116.3
4	TOW1	50	1.5	0.197	0.511	0.78	67.2
Driegen	TOW2	50	1.5	0.198	0.509	0.78	68.7
(1986)	TOW3	50	1.5	0.284	0.528	0.78	81.8
	TOW4	50	1.5	0.111	0.458	0.78	50.2
	TOW5	50	1.5	0.110	0.459	0.78	49.5
	TOW6	50	1.5	0.363	0.554	0.78	89.4
	TOW7	50	1.5	0.397	0.571	0.78	81.3
	TOW8	50	1.5	0.490	0.588	0.78	91.9
	TOW9	50	1.5	0.592	0.622	0.78	90.7
	TOW10	50	1.5	0.278	0.420	0.78	88.8
	TOW11	50	1.5	0.301	0.596	0.78	90.3
	TOW12	50	1.5	0.115	0.514	0.78	52.9
	TOW13	50	1.5	0.486	0.653	0.78	100.4
	TOW14	50	1.5	0.105	0.393	0.78	46.5
	TOW15	50	1.5	0.451	0.451	0.78	89.7
	TOW16	50	1.5	0.263	0.786	0.78	103.5
	TOW17	50	1.5	0.405	0.560	0.78	93.2
	TOW18	50	1.5	0.493	0.861	0.78	150.7
	TOW19	50	1.5	0.087	0.763	0.78	39.8
	TOW20	50	1.5	0.291	0.516	0.78	78.4
	TOW20-2	50	1.5	0.288	0.521	0.78	80.0
	TOW21	50	1.5	0.111	0.440	0.78	48.7
	TOW22	50	1.5	0.196	0.497	0.78	65.3
	TOW22-2	50	1.5	0.260	0.565	0.78	86.5
	TOW23	50	1.5	0.302	0.586	0.78	87.3
	TOW23-2	50	1.5	0.200	0.487	0.78	67.4
	TOW24	50	1.5	0.301	0.588	0.78	84.6
	TOW25	50	1.5	0.200	0.486	0.78	72.2
	TOW26	50	1.5	0.405	0.660	0.78	104.2
	TOW27	50	1.5	0.201	0.484	0.78	68.2
	TOW29	50	1.5	0.301	0.588	0.78	91.6
	TOW30	50	1.5	0.200	0.493	0.78	69.5
5	TOW31	50	1.125	0.208	0.495	0.78	65.3
Driegen	TOW32	50	1.125	0.204	0.488	0.78	65.0
(1986)	TOW33	50	1.125	0.306	0.582	0.78	86.9
6	TOW34	50	0.5	0.211	0.456	0.78	55.0
Driegen	TOW35	50	0.5	0.328	0.542	0.78	75.6
(1986)	TOW36	50	0.5	0.209	0.459	0.78	54.7
	TOW37	50	0.5	0.120	0.417	0.78	30.8
	TOW38	50	0.5	0.209	0.460	0.78	55.8
	TOW39	50	0.5	0.436	0.611	0.78	90.4
7	TOW49	50	1.125	0.178	0.549	0.66	71.6
Klaassen	TOW50	50	1.125	0.337	0.633	0.66	116.2
(1990)	TOW51	50	1.125	0.402	0.663	0.66	131.0
	TOW52	50	1.125	0.349	0.611	0.66	113.7
	TOW53	50	1.125	0.189	0.517	0.66	68.4
	TOW54	50	1.125	0.091	0.488	0.66	29.5

* Mixture of three well sorted size fractions: fine $D_{50} = 0.68$ mm, medium $D_{50} = 2.1$ mm and coarse $D_{50} = 5.7$ mm.

Figure 20 shows that there is no difference between the two definitions of mean bedform height. The data points are very close to the line of perfect agreement. This is also what we would expect, since all crest and trough locations are the same in the determination of $\overline{\Delta_s}$ and $\overline{\Delta_l}$. This means that the sum of vertical distances between crests and troughs is equal for both definitions and therefore also the mean bedform height.

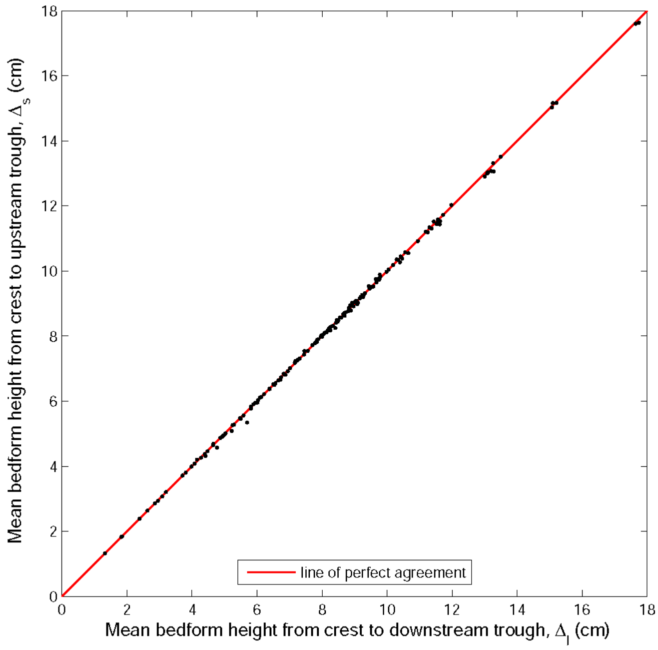


Figure 20: Comparison between $\overline{\Delta_s}$, the mean bedform height determined as the vertical distance from crest to upstream trough, and $\overline{\Delta_l}$, the mean bedform height determined as the vertical distance from crest to downstream trough.

4.2 Mean bedform length

For the mean bedform length, the same result is found. There is no difference between the mean bedform lengths $\overline{L_c}$, which is the distance between two subsequent crests, and $\overline{L_t}$, which is the distance between two subsequent troughs. This is also valid for the mean bedform length determined as the distance between subsequent upcrossings, $\overline{L_{upcr}}$, and the mean bedform length determined as the distance between subsequent downcrossings, $\overline{L_{downcr}}$. All four definitions result in the same mean value for the bedform length.

4.3 Standard deviation of bedform height

Figure 21 shows the comparison between the standard deviation of bedform height determined as the vertical distance from crest to upstream trough, σ_{Δ_s}, and the standard deviation of bedform height determined as the vertical distance from crest to downstream trough, σ_{Δ_l}. Note that the data points deviate significantly from the line of perfect agreement. The standard deviation of bedform height is smaller when using the definition of distance between crest and downstream trough. This might be explained by the presence of a flow circulation zone downstream of a dune. The size of the flow separation zone is strongly related to the height of the bedform, Δ_l (e.g. Allen, 1965). Allen (1965) found that the horizontal distance between crest and reattachment point is related to bedform height, defined as the distance from crest to subsequent trough. This suggests that there is more correlation between a crest and its downstream trough – and a smaller standard deviation – than there is between a crest and its upstream trough. As a result, researchers commonly use as a definition for bedform height the vertical distance between a crest and its downstream trough.

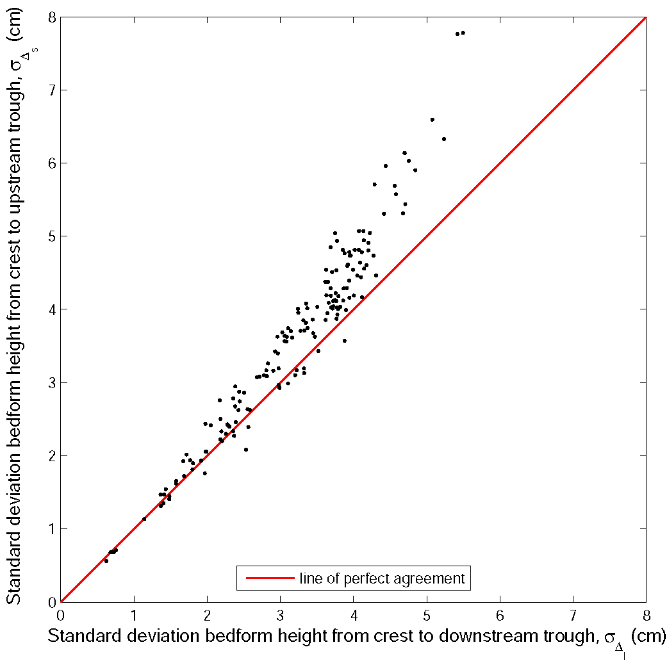


Figure 21: Comparison between σ_{Δ_s}, the standard deviation of bedform height determined as the vertical distance from crest to upstream trough, and σ_{Δ_l}, the standard deviation of bedform height determined as the vertical distance from crest to downstream trough.

4.4 Standard deviation of bedform length

Figure 22 presents the comparison between the standard deviation of bedform length defined as the horizontal distance between two crests, σ_{L_c}, and the horizontal distance between two troughs, σ_{L_t}. Figure 22 shows that the standard deviation is larger for the distance between troughs than for the distance between crests. This may be explained by the presence of wide troughs in the case of isolated bedforms (Figure 19). In that case, the BTT finds the trough location somewhere within the wide trough. The location of the trough may deviate more than the location of the crest. It is recommended not to use the distance between troughs for the computation of bedform length.

Figure 23 shows that there is not much difference between the standard deviation of the horizontal distance between upcrossings ($\sigma_{L_{upcr}}$) and the standard deviation of the horizontal distance between downcrossings ($\sigma_{L_{downcr}}$).

Figure 24 shows that the standard deviation of the horizontal distance between crests (σ_{L_c}) is smaller compared to the standard deviation of the horizontal distance between upcrossings ($\sigma_{L_{upcr}}$).

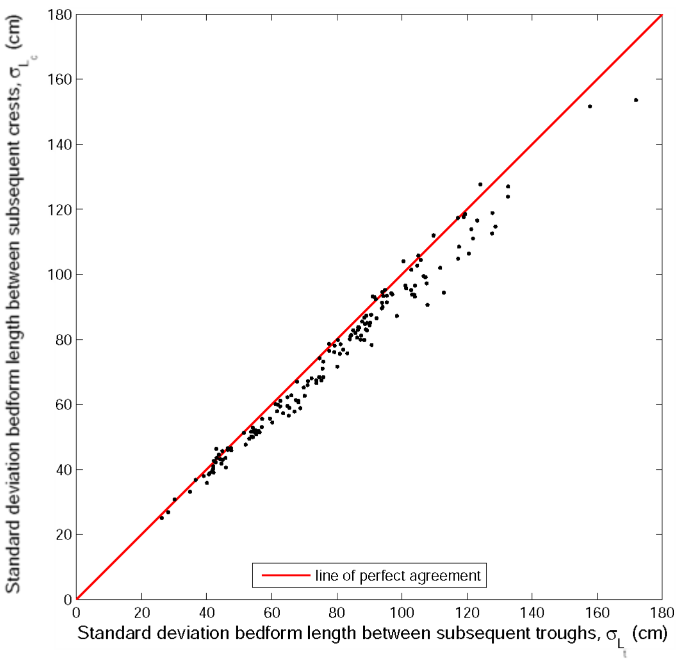


Figure 22: Comparison between σ_{L_c}, the standard deviation of bedform length determined as the horizontal distance between two subsequent crests, and σ_{L_t}, the standard deviation of bedform length determined as the horizontal distance between two subsequent troughs.

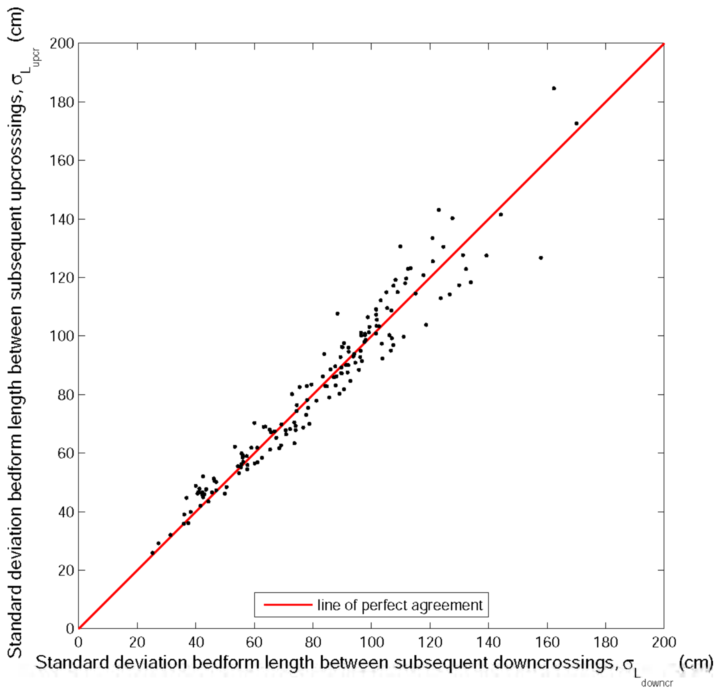


Figure 23: Comparison between $\sigma_{L_{upcr}}$, the standard deviation of bedform length determined as the horizontal distance between two subsequent upcrossings, and $\sigma_{L_{downcr}}$, the standard deviation of bedform length determined as the horizontal distance between two subsequent downcrossings.

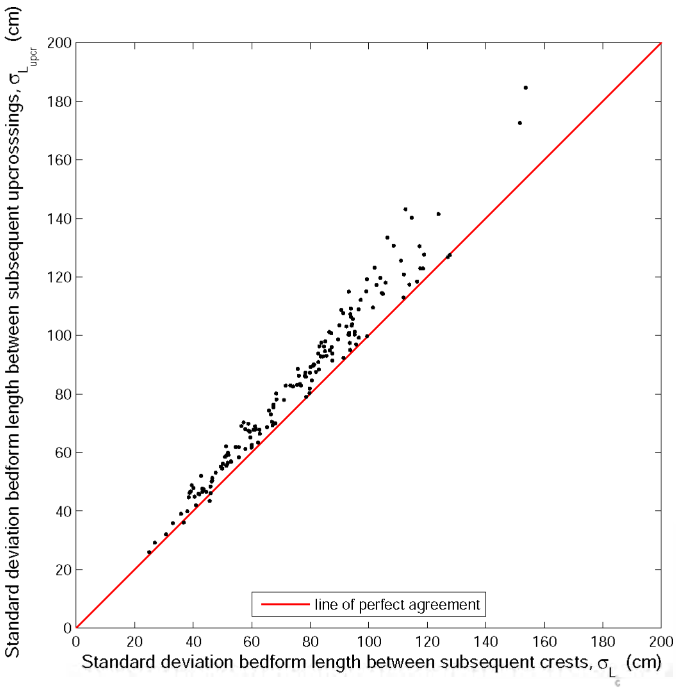


Figure 24: Comparison between $\sigma_{L_{upcr}}$, the standard deviation of bedform length determined as the horizontal distance between two subsequent upcrossings, and σ_{L_c}, the standard deviation of bedform length determined as the horizontal distance between two subsequent crests.

5 Conclusions

1. We wrote a numerical code which is able to select crests and troughs in a measured bed elevation profile and to determine the following bedform characteristics of individual bedforms and their means and standard deviations:

   - Crest elevation (η_c)
   - Trough elevation (η_t)
   - Height of stoss side (Δ_s)
   - Height of lee side (Δ_l)
   - Length of stoss side (L_s)
   - Length of lee side (L_l)
   - Bedform length between crests (L_c)
   - Bedform length between troughs (L_t)
   - Bedform length between upcrossings (L_{upcr})
   - Bedform length between downcrossings (L_{downcr})
   - Steepness of lee side (S_{lee})

2. So far, the code has been used successfully to determine bedform dimensions of various sets of flume experiments, field measurements in river and marine environments.

3. The code is able to determine if more than one dominant bedform length is present in the bed elevation profile, and to determine the bedform characteristics of more than one bedform length of interest. However, here is room for improvement.

4. The code is written such that as few as possible subjective choices have to be made for determining bedform dimensions. There are four quantitative subjectivities in the code. However, for the data sets we analyzed so far, these four values can be kept the same.

5. It is recommended to use the vertical distance between a crest and its downstream trough as a definition of bedform height.

6. It is recommended not to use the horizontal distance between two subsequent troughs as a definition of bedform length.

6 Recommendations

1. The BTT can be made more user-friendly. For instance, we can give the user advice on how the format of the raw data should be, or indicate whether the data set is sufficiently accurate.

2. In the BTT we give the possibility to use a moving average technique to detrend the data. May be, other techniques are more suitable to detrend a bed elevation profile.

3. A flume experiment can have secondary bedforms. In such a case, it would be desirable to use both a linear trend line and a moving average trend line to study both bedform types. This is not possible in the current version of the BTT.

Acknowledgements

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A Determination of the trend line

A.1 Introduction

In laboratory flumes we usually detrend a bed elevation profile (BEP) by fitting a best fit linear line through the BEP and subtract this line from the BEP. Field measurements of bed elevations in a river cannot be treated in the same way. Especially when the BEP under consideration is long (several kilometers), the mean river bed is usually a fluctuating line rather than a linear line (Figure 25).

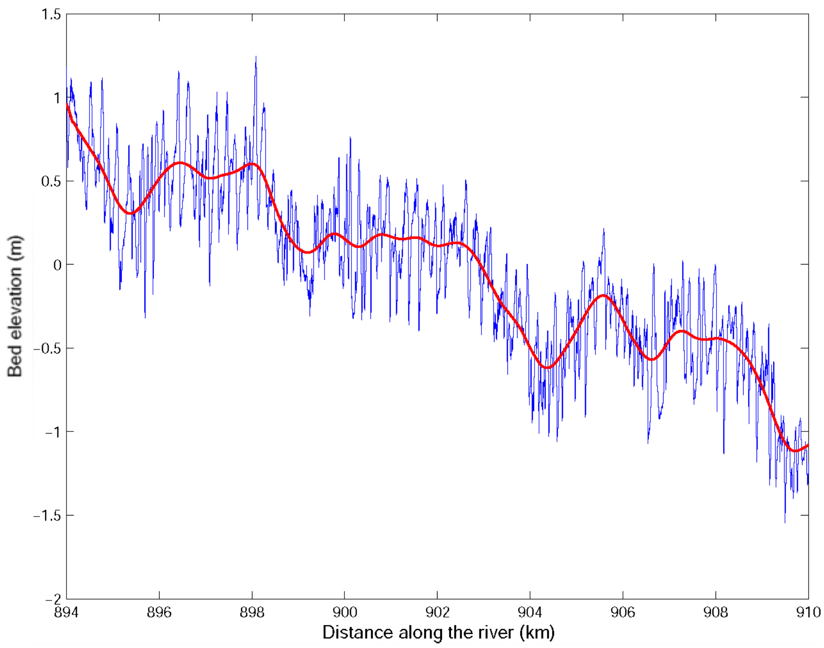


Figure 25: The mean river bed is a fluctuating line rather than a linear line. BEP of a part of the Waal River is shown.

For a case as in Figure 25, it is not desirable to determine a trend line manually, as a manual procedure is a subjective procedure and it needs to be done for each BEP. Determination of such a trend line will therefore be done using a moving average procedure. The only unknown input parameter is the span, the amount of data points that is used to average in the moving average technique. The span (P_0) we are looking for depends on the dominant bedform type and the distance between two subsequent measured data points.

A.2 Determination of the trend line span

A.2.1 Steps to determine the trend line span

In the bedform tracking tool (BTT) we determine the trend line span as follows:

- For a span value, varying from 3 data points through N data points, we determine a weighted moving average trend line of the BEP. Here N is the total amount of data points the BEP consists of. For instance, the weighted moving average trend line drawn in Figure 25 is determined using a moving average technique. The span must be odd. Using a span of 1 yields a trend line that is equal to the original BEP. We use a Hann window for the weights of the span.
- We subtract the moving average trend line from the original BEP which yields a detrended BEP.
- We use a spectral density function to find the peak bedform length in the detrended BEP.
- We plot the peak bedform length against the trend line span.
- The graph of peak bedform length against span gives information on the bedform lengths that are present in the original BEP. The user can specify which bedform lengths he/she is interested in. The span corresponding to these bedform lengths is used to determine the trend line. This span is located at 0.4 times the length of the sill (just left of the center of the sill).

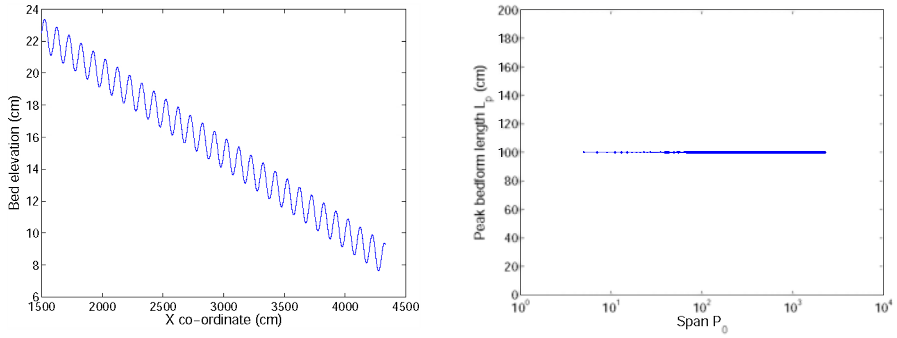
In the next section we illustrate these steps with a few examples.

A.2.2 Illustration of the steps

We use four examples to illustrate how we determine the trend line span in the BTT:

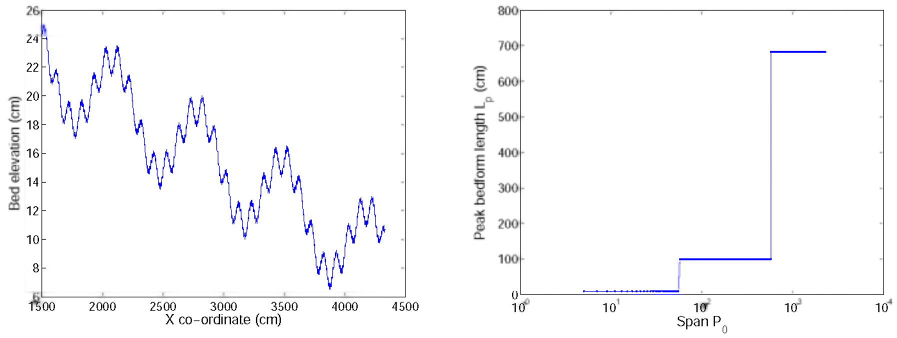
1. A sine wave added to a linear line. Bedform length is 100 cm.
2. Three sine waves with different bedform lengths added to a linear line. Bedform lengths are 10 cm, 100 cm and 700 cm, respectively.
3. A field measurement of the Waal River.
4. A flume experiment of Blom *et al.* (2003)

Figures 26a, 27a, 28a and 29a show the BEPs of the four examples 'one sine', 'three sines', the Waal River and the flume experiment. Figures 26b, 27b, 28b and 29b show the peak bedform length against trend line span for the four examples. Such a graph is the result after the fourth step.



(a) (b)

Figure 26: Illustration of the determination of dominant bedform lengths for example 1. a) Bed elevation profile schematized as a sine wave added with a linear trend. b) Peak bedform length against the span. The horizontal part (sill) indicates the bedform length.

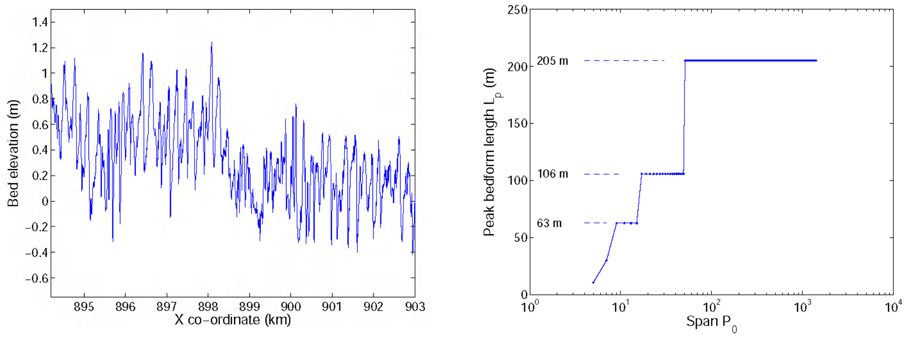


(a) (b)

Figure 27: Illustration of the determination of dominant bedform lengths for example 2. a) Bed elevation profile schematized as three sine waves added with a linear trend. b) Peak bedform length against the span. The horizontal parts (sills) indicate the bedform lengths.

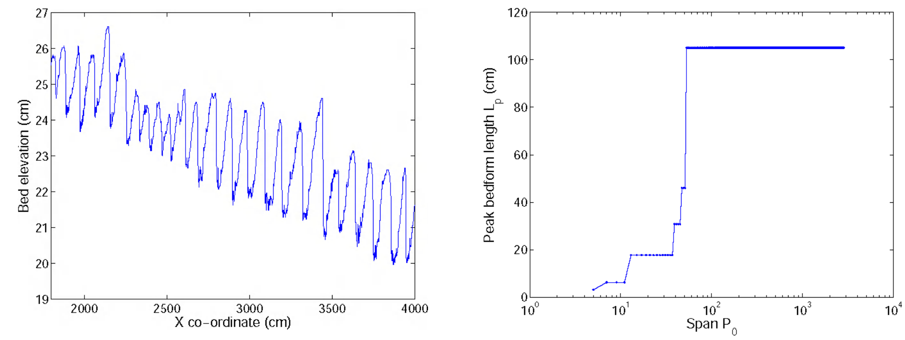
The horizontal parts in a 'peak length versus trend line span' graph indicate which bedform lengths are present in a BEP. We call these horizontal parts 'sills'. The amount of sills indicate the amount of dominant bedform lengths. Figure 26b, corresponding to one sine wave, shows one sill at $L =$ 100 cm. Figure 27b, corresponding to the example with three sine waves added, shows three sills at $L_1 = 10$ cm, $L_2 = 100$ cm, and $L_3 = 700$ cm. Figure 28b, corresponding to the Waal River, shows three sills. Figure 29b, corresponding to the flume experiment, shows two sills.

In the last step the user of the BTT has to specify which bedform length he/she is interested in. The user chooses a bedform length, the BTT will then use the corresponding span value to determine the moving average



(a) (b)

Figure 28: Illustration of the determination of dominant bedform lengths for example 3. a) Bed elevation profile of a part of the Waal River. b) Peak bedform length against the span. The horizontal parts (sills) indicate the bedform lengths.



(a) (b)

Figure 29: Illustration of the determination of dominant bedform lengths for example 4. a) Bed elevation profile of a flume experiment. b) Peak bedform length against the span. The horizontal parts (sills) indicate the bedform lengths.

trend line. To help the user, the BTT plots the peak bedform length versus span' graph, and writes the dominant bedform lengths on the screen. Furthermore, the BEP is plotted, together with the moving average trend lines. The span value corresponding to a certain bedform length is determined by taking the span value just left of the center of each sill (at 0.4 of the sill length). To illustrate the last step, we use the four examples. Figure 30a shows the span values that correspond to the three bedform lengths. Figure 30b presents the three trend lines corresponding to the three span values. The user has to select one or more of the trend lines by specifying the bedform length(s) of interest. Likewise, Figures 31a and 32a shows the span values of the Waal River and flume experiment, respectively. Figures 31b, 31c, 31d and 32b and 32c show the BEPs of the Waal River and flume experiment together with the trend lines.

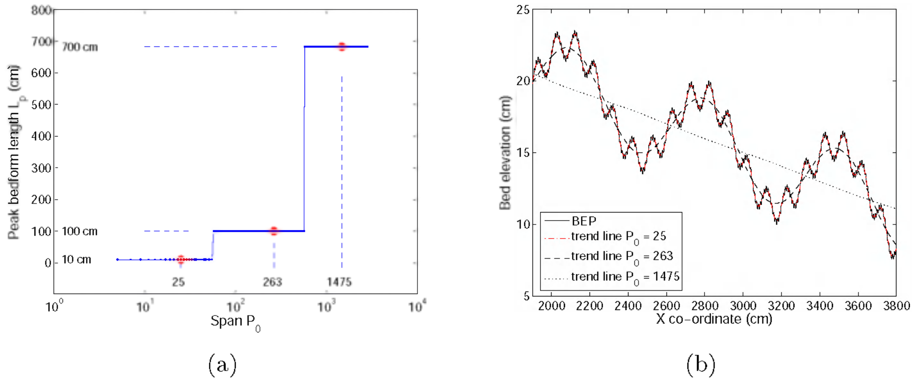


Figure 30: Illustration of the trend lines corresponding to dominant bedform lengths for example 2. a) Peak bedform length against the trend line span. The horizontal parts (sills) indicate the dominant bedform lengths. b) Original BEP together with the trend lines (dashed) determined with a span of $P_0 = 25$, 263 and 1475.

A moving average technique is not able to perform near the boundaries of a BEP, as close to the boundary there are not enough data points available to compute the average of a certain amount of data points. As such, close to the boundaries the moving average trend line is disturbed. We only take into account the part of the BEP that is not disturbed.

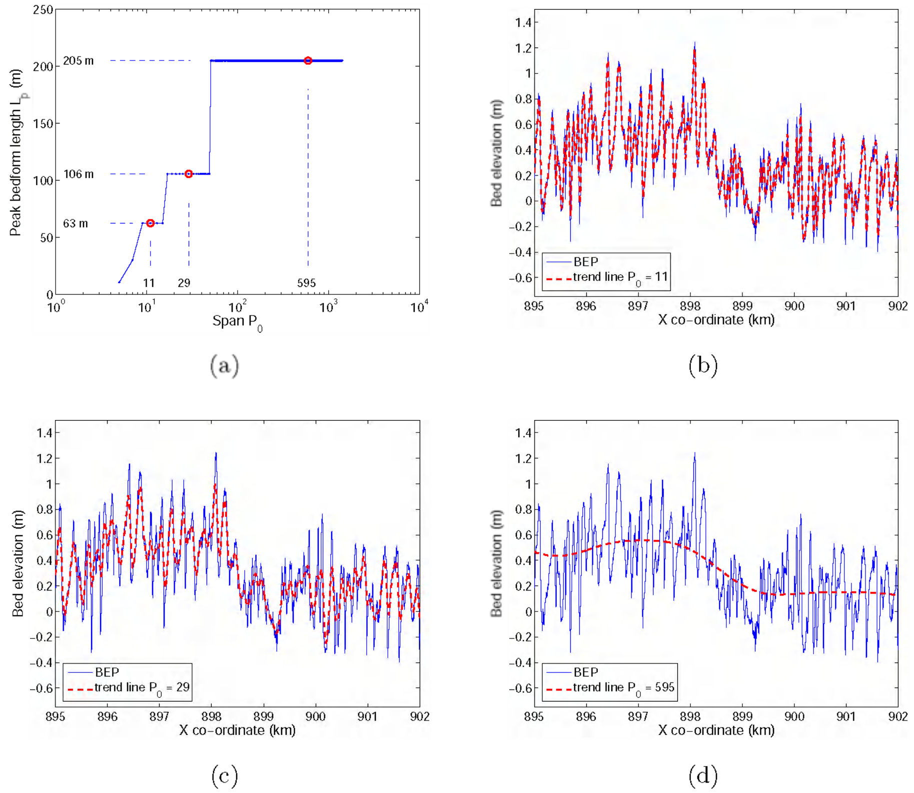
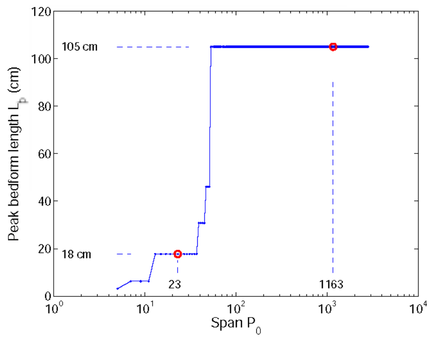
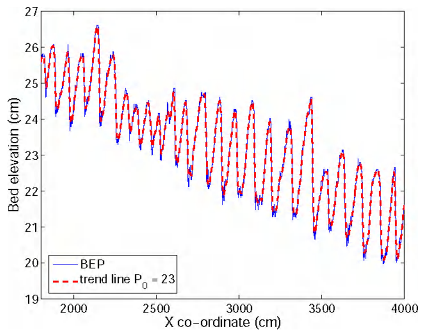


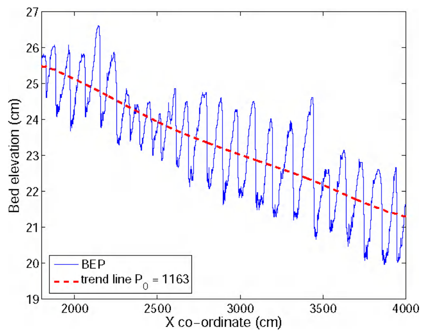
Figure 31: Illustration of the trend lines corresponding to dominant bedform lengths for example 3. a) Peak bedform length against the trend line span. The horizontal parts (sills) indicate the dominant bedform lengths. b) Original BEP together with the trend line (dashed) determined with a span of $P_0 = 11$. c) Original BEP together with the trend line (dashed) determined with a span of $P_0 = 29$. d) Original BEP together with the trend line (dashed) determined with a span of $P_0 = 595$.



(a)



(b)



(c)

Figure 32: Illustration of the trend lines corresponding to dominant bedform lengths for example 4. a) Peak bedform length against the trend line span. The horizontal parts (sills) indicate the dominant bedform lengths. b) Original BEP together with the trend line (dashed) determined with a span of $P_0 = 23$. c) Original BEP together with the trend line (dashed) determined with a span of $P_0 = 1163$.

B Sensitivity of the filter span constant

In Figures 7 and 8 we show that the value of the filter span constant influences resulting bedform heights and bedform lengths. If we use a filter span constant $C = 1/40$, small features crossing the zero line are considered in the analysis, whereas if we use a filter span constant of $C = 1/2$, some individual bedforms are overlooked. As a result, mean bedform length and mean bedform height increase with increasing filter span constant. We illustrate this for some flume experiments of Leclair (2002) and Blom *et al.* (2003) in the Figures 33 and 34, respectively.

We plotted mean bedform height against the filter span constant. The flume experiments of Leclair in Figure 33 show a rapid increase for small values of the filter span constant ($1/20 < C < 1/6$), and a less rapid increase for large values of the filter span constant ($C > 1/6$). The rapid increase belongs to the effect that fewer and fewer small features are considered in the analysis with increasing filter span constant. The gradual increase belongs to the effect that the filtered BEP deviates more and more from the original BEP, so that more and more bedforms are overlooked. We have chosen a filter span constant that lies between the 'rapid increase' and the 'gradual increase'. We use a filter span constant of $C = 1/6$ in the BTT, which is indicated in the Figures 33 and 34 with the dashed vertical line.

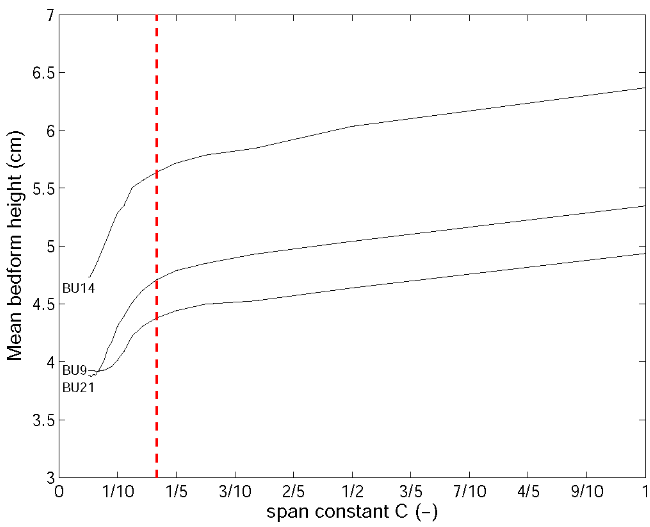


Figure 33: Mean bedform height against filter span constant C for three flume experiments of Leclair (2002). The filter span constant is varied from 1/20 to 1. The vertical dashed line indicates a filter span constant of 1/6, which we use in the BTT.

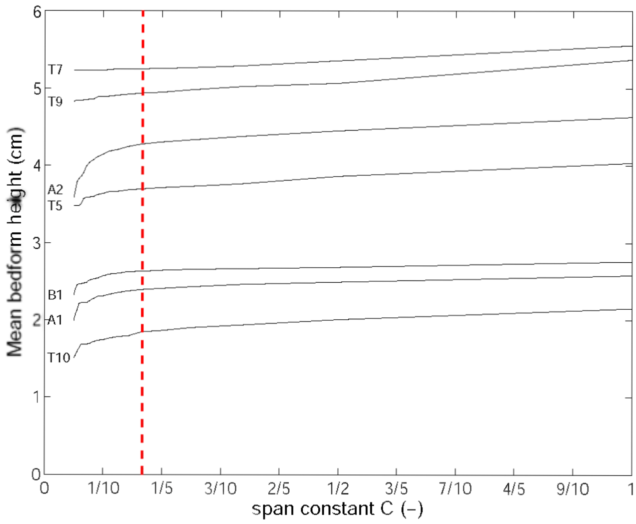


Figure 34: Mean bedform height against filter span constant C for some of the flume experiments of Blom *et al.* (2003). The filter span constant is varied from $1/20$ to 1. The vertical dashed line indicates a filter span constant of $1/6$, which we use in the BTT.