Reply to the Anonymous Referee #1

Dear Referee,

We thank you for your comments, which will help improve the clarity of the manuscript as well as the choice of the methods.

According to both reviews we decided to make very substantial changes to the paper. This work is a methodological study that introduces relatively new wavelet analysis tools in the field of geomorphic analysis (namely, Wavelet Ridge Extraction), in order to identify the pseudo-periodicity of alternating morphological units from a general point of view (and not only pool-riffle morphology). We did initially introduce an index method as a benchmark, but this index was poorly designed due to a lack of physical basis for the choice of the variables. We also neglected some relevant literature on the identification of the morphological units using DEMs, which could be used as benchmark methods in this paper.

For that, we suggest changing the title of this paper to "***Automatic identification of alternating morphological units in river channel using wavelet analysis and ridge extraction***". This will be more general and focuses on the method and not on the pool-riffle morphology.

We have presented two methods in this article. The first one is the wavelet method which represents alternating morphological units (pools and riffles) as pseudo-periodic signals with a continuous wavenumber function K(x). The other one is the index method which is a benchmark method that gives a discrete identification of the morphological units.

With the suggestion of the second reviewer Prof. Gregory Pasternack, we will cut out the index method. We will focus only on the wavelet analysis and ridge extraction in the univariate and the multivariate cases and compare its results with the benchmark method: BDT (O'Neill and Abrahams, 1984) to the bed elevation data. We didn't compare it with other recent methods (e.g. Hauer et al., 2009; Wyrick et al., 2014) because they require thresholds (expert judgment) collected from the field, which is not possible in our case.

We will also minimize the use of modeled variables and apply the methods directly on field measurements (velocity, hydraulic radius variables at the lowest surveyed water level and planform curvature angle). We will use modeling results (Fluvia model) for bed shear stress only, as the energy slope cannot be determined in a sufficiently accurate manner with the measurements.

For the literature, we missed many recent studies and methods in relation to this work. So first we will add a table that summarizes examples of methods of identifying these morphologies and the variables chosen to do that. Second, we will change and add many recent works especially those working with meter-resolution digital elevation models (DEMs). Finally, we will clearly state the objectives of this study in the abstract and in the introduction.

Another important thing is that we propose a new structure of the paper:

I- Introduction:

First, we will state the scope of this study with adding more fields of its application. Second, we will introduce a literature review of metrics, variables used to identify and characterize the alternating morphological units. We will focus on two kinds of numerical criteria computed at reach scale:

- The distribution of spacings between morphological units (mean, mode, etc.),
- After computing the mean values of geometrical and flow properties (velocity, hydraulic radius, bed shear stress, etc.) in each class of morphological units (e.g. pools, riffles, runs, etc.) we will evaluate the covariance matrix of these parameters.

1) State of art methods for a quantitative assessment of morphological variability within a reach:

We will present some recent methods and works in the identification of these alternating morphological units (pool-riffle in our case) and state their objectives and limitations. We will start with the Bedform Differencing Technique (BDT, O'Neill and Abrahams, 1984), which is simple but uses bed elevation as the sole variable, and relies on a tolerance criterion on elevation differences. We will then review index methods like Mesohabitat Evaluation Model (MEM, Hauer et al., 2009) which classify each position in the reach into a given discrete morphological unit (pool, riffle, run, plane bed, etc.). These methods rely on expert judgement to define the thresholds that define parameter classes. Finally, geostatistical methods (e.g. Legleiter, 2014) give a continuous description of river channel properties in spatially stationary way, using longitudinal and transverse variography. For these reasons, we are searching for a method that gives a continuous description of geometrical and flow characteristics along the reach with a non-stationary description.

2) Study objectives

We will state that this work aims to introduce relatively new wavelet analysis tools in the field of geomorphic analysis, the Wavelet Ridge Extraction, in order to identify the pseudo-periodicity of alternating bedforms from a general point of view. In this study we will use a dataset that presents mainly pool-riffle morphologies, but the method can be applied to any morphology.

We will present the scheme of the paper which include a methodological section of the wavelet analysis and ridge extraction in the univariate and the multivariate cases, a section that presents the comparison between our method and the BDT, a discussion section, and conclusions.

II- Data set and study reaches:

We will present the six reaches, more explicit information about data collection, planform curvature angle computing and about the numerical modeling (Fluvia).

III- Wavelet method

1) Wavelet analysis and ridge extraction:

We will present a general introduction about wavelets including some methods such as the Wavelet Transform Modulus Maximum (WTMM, Gangodagamage et al., 2007) and other studies using the wavelets in the geomorphological field (Lashermes et al., 2007; McKean et al., 2009). Procedures such as the WTMM (Muzy et al., 1993) consist in extracting components of the signal, but they are not specifically designed to identify pseudo-periodic components in a univariate, let alone in a multivariate case. For this reason, we introduce the procedure called Wavelet Ridge Extraction (Lilly and Olhede, 2009).

2) Univariate case

We will present the methodology of this method in the univariate case using one of the four variables (velocity, hydraulic radius, bed shear stress, and planform curvature angle).

3) Multivariate case

We will present the methodology of this method in the multivariate case using the four variables (velocity, hydraulic radius, bed shear stress, and planform curvature angle).

IV- Results

1) Univariate vs Multivariate:

We will compare the univariate with the multivariate results with computing some statistics. And we will use the multivariate wavelength to model the bed elevation of the reaches without using it as a variable.

2) Comparison with the benchmark method

We will compare our method's results in the multivariate case with the selected benchmark method from the literature: BDT.

V- Discussion

We will discuss results (longitudinal spacing, number of morphological units, etc.) with literature and with the benchmark method.

VI- Conclusions

Kind regards,

The authors

Major comments:

The manuscript "Wavelet and index methods for the identification of pool–riffle sequences" by Mahdade et al. presents two novel methods for the identification of pools and riffles in natural streams. These methods also allow the assessment of the main geometrical features of pools and riffles. The manuscript states that appropriate geometric description of pools and riffles is pivotal for flood modelling. I think this statement is correct when modelling floods (and flash floods) at the local scale. Conversely, previous studies have shown that simplified representations of river geometry can be a cost-effective solutions for flood modelling at the large (basin to continental scale). In fact, I believe that an accurate representation of river geometry is essential for the implementation of hydrodynamic models used for the investigation of local flow conditions and sediment transport. The scope of the paper could thus be extended to biological and environmental modelling (oxygen exchange, fish habitat, sediment transport) and not only limited to flood forecasting.

Response:

We agree with you that this statement is correct only at local/small scale, in which we can quantify geometric variability and especially alternating morphological units. In the new version of the paper, we will add examples of application of our study such as the design of a synthetic river topography which is implemented in river restoration (e.g., Wheaton et al., 2004a), habitat modeling, ecohydraulics (e.g., Pasternack and Brown, 2013), biological and environmental modeling (oxygen exchange, fish habitat …) and also that this variability controls fluvial processes as sediment transport, but not focusing only on flood forecasting.

The paper is interesting, sections 1 and 2 provide a comprehensive literature review; sections 4 and 5 provide a detailed explanation of the methodologies; the presentation and discussion of the results in section 6 is quite extensive. However, I think that a number of major modifications should be introduced before the publication of this study.

Firstly, I think that the research gap and the novelty of this study should be clearly stated. Why did the authors propose two novel methods for the identification of pools and riffles? What are the advantages of these two novel methodologies when compared to the existing ones? I believe that these aspects should be clearly stated in the manuscript.

Response:

The goal of the paper is to introduce a new method for the analysis of river morphology. The rationale behind the method is that the existence of alternating morphological units along a reach (such as pools-riffles sequences, or step-pool etc.) should translate as a *pseudo-periodicity* in geometric and flow variables. Hence, identifying these bedforms amounts to identifying a local wavenumber K(x) and phase ϕ(x) for each variable, a task that can be performed by wavelet analysis and especially Wavelet Ridge Extraction (Mallat, 1999; Lilly and Olhede, 2010), in a multivariate framework.

In the initial version of the paper, we were comparing this wavelet-based method with two benchmark methods: the BDT (O'Neill and Abrahams, 1984), and an index method that consists in affecting a different numerical value for each class of a given variable/degree of freedom, and then sum these individual index functions into a composite one.

The second reviewer Prof. Gregory Pasternack has raised major concerns not about the index method in itself, but on the choice of the variables/degrees of freedom. Initially we used the first three axes of a Principal Component Analysis as the degrees of freedom, a choice which has very little physical meaning. We will entirely ignore this choice and use a classical variables/degrees of freedom, which are velocity, hydraulic radius (or the closely related cross-sectional averaged depth), bed shear stress in addition to the new variable: planform curvature angle.

However, we intend to keep the last benchmark, the BDT method, as it is in the current version of the paper instead of adding other recent methods (e.g. Hauer et al., 2009; Wyrick et al., 2014) because they require thresholds (expert judgment) collected from the field, which is not possible in our case.

Second, the results of the new methods are compared to the results of the BDT method. Is the BDT method used as benchmark or to validate the new methods? Is the BDT method considered more accurate than the new methods? If so, why? What are the advantages of using the two methods rather than using the BDT method? Would it be possible to validate the results of this study using field data?

Response:

In this study, we consider the BDT method as a benchmark method. We do not consider a specific method to be the "true" or "reference" one, we only apply several methods to have a general idea on the uncertainties in the identification of morphological units. That being said, there is a substantial difference between the BDT and index methods on one side, and the wavelet ridge extraction on the other side:

- BDT and index methods classify each position in the reach into a given category (pool, riffle, run, plane bed, etc.); hence, in 1D, we have access to a discrete values of bedform lengths L_i (i=1…N), and we can compute statistics of this discrete distribution such as ***mean***, ***mode***, ***n-th order moments***, etc.;
- In contrary, the wavelet ridge extraction provides a continuous description of bedform spacing along the reach, through a continuous wavenumber function K(x). In turn, we can compute the statistics (again, mean, mode, n-th order moments, etc.) of this function in order to compare them with the values obtained in a discrete method.

Moreover, index methods use expert judgement in order to specify threshold values for each variable/degree of freedom. Since wavelet analysis is continuous in nature, such thresholds are not needed in our method.

Third, the computation of the index method relies on the results of the numerical model. Have the authors considered the impact of the uncertainties in the results of the numerical model on the results of the index method?

Response:

The use of model outputs is indeed a questionable choice that may add a lot of uncertainty in the results. The purpose of the numerical model used in the previous studies by Navratil et al. (2006) was simply to generate water surface profiles for discharge values other than the surveyed ones (i.e., interpolate/extrapolate the rating curves). In our revised paper, we will solely rely on measurements at the lowest surveyed discharge. However, since the calibration of the FLUVIA model on the reaches provides estimates of Manning coefficient n, we will use these values in order to compute the third degree of freedom, bed shear stress $\tau_b(x)$, along the reach: even if partly relies on calibration, it seems a more robust way of computing τ_b than through the finite differentiation of the total head function $U^2/2g + z_{surface}$ between adjacent cross-sections to get the energy slope J.

Furthermore, I suggest discussing the transferability of the new methods to other reaches. In other words, how easy would be to implement the proposed methodologies to other study areas? Are the data and algorithms required easy to collect and implement? Can other researchers implement the proposed methodologies?

Response:

As stated previously, the wavelet methods intends to be quite general and can be applied in any morphology that presents alternating bedforms (pool-riffle, step-pool, etc). The code comes in the form of a small number of Matlab functions, and the data has to be provided as values of flow variables sampled at successive locations along the reach. The choice of the set of variables/degrees of freedom is up to the user, in our case we chose the set [U(x) , Rh(x), $\tau_b(x)$, $\theta(x)$] but we could pick other variables.

Moreover, I think the manuscript should clearly state which methods are recommended. A more explicit presentation of the conclusions of this study would highlight its scientific and practical relevance.

Regarding the structure of the paper, I would like to recommend two modifications: - Section 2 lists a large number of studies and it is a bit hard to follow. More specifically, I think it is difficult to appreciate the differences between the large number of criteria listed in this section. The authors might consider adding a table to summarise their literature review.

I hope the authors will find my questions and recommendations useful to improve their manuscript.

Response:

As said before, the structure of the paper will be changed by splitting the results and discussion and adding a conclusions part, the later one will specify the added value of the wavelet method according to the comparison in the discussion section. In fact, we will compare the metrics computing (mean, mode, n-th order moments, etc of the distribution) using the two methods.

Minor comments:

I listed below a number of minor recommendations.

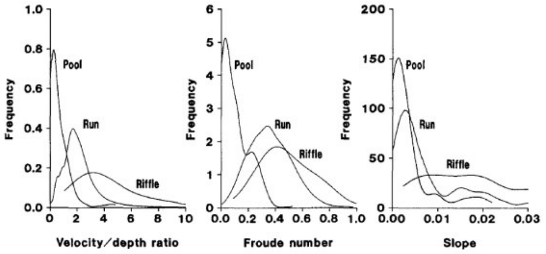
Comment of the reviewer	**Response of the authors**
Page 1, lines 7-8: the sentence "To better take this high-frequency variability in bedforms into account in hydraulic models" is a bit convolute. The authors might consider improving the structure of this sentence.	We will replace it with: "To include/consider this high-frequency variability of the geometry in the hydraulic models"
Page 1, abstract: the abstract should clearly state the research gap, the aim, and the novelty of the study.	We will change the abstract by including that this work is a methodological study that introduces relatively new wavelet analysis tools in the field of geomorphic analysis (namely, Wavelet Ridge Extraction), in order to identify the pseudo-periodicity of alternating morphological units from a general point of view (and not only pool-riffle morphology). We will state clearly the aim of this paper which is for example extracting some quantitative properties of these alternating bedforms such as the mean and the mode of their longitudinal spacings, with a "continuous" vision of the topography instead of a discrete classification.
Page 1, line 9: the abstract mentions "several methods", however, only three (two novel methods and one benchmarking method) are listed explicitly.	As stated above, we will clarify the presentation: we introduce one new method (wavelet ridge extraction) in univariate and multivariate cases and we compare the results with an existing method (BDT).
Page 1, lines 12-13: the authors might consider avoiding the repetition of the word "compared".	Corrected
Page 2, lines 14-15: I am not sure whether this is the final format of the paper, however, I suggest positioning each figure after a full stop (Figure 1 is currently positioned in the middle of a sentence).	This is not the final format of the paper. We will change that in the revised version.
Page 2, line 15: please correct "dimensionless reach wavelength".	Corrected
Page 3, lines 4-5: this sentence is a bit hard to understand. Do the authors mean that the overarching purpose of their study is to provide a methodology for the prediction / modelling / assessment of cross sections variability?	We will cut out this sentence and change from line 14 to 16 in page 2 with: "In this study, we focus mainly on alternating alluvial channels especially pool-riffle sequences, even though the method presented here could be used to analyze any alternate morphological units (MUs). The objective is to provide a continuous description of geometric and flow patterns along a reach, a description that could be subsequently used to create a synthetic river as in the RiverBuilder (Brown et al., 2014). To do that we calculate the dimensionless reach

	wavelength λ^*, which is the distance…”.
Page 3, line 8: words such as “methods” or “techniques” might be more appropriate than “studies”.	Corrected
Page 3, line 11: could please the authors clarify the meaning of “descriptions of the water surface characteristics”? Is “water surface slope” (mentioned in Line 8) included in this latter category?	Descriptions of the water surface characteristics means a method that describe pools and riffles from the combination of all characteristics of the water surface (water surface elevation, water surface slope, etc.) and which include effectively the slope as Mosely (1982) mentioned in his paper. We also corrected the reference. *“Mosley, M. P. (1982). Procedure for characterising river channels, Water Soil Misc.”* Instead of *“Mosley, M. P.: Analysis of the effect of changing discharge on channel morphology and instream uses in a braided river, Ohau River, New Zealand, Water resources research, 18, 800–812, 1982.”*
Page 3, line 14: I suggest clarifying the sentence “because it changes less with discharge”.	It means that this morphological definition of pool-riffle sequences doesn’t depend on discharge.
Page 3, line 20: please rephrase “goes with the notion”.	We will change it with “involves the use”
Page 3, line 22: please rephrase “allows one to extract”.	We will change it with “extract”
Page 3, line 30: please rephrase “using a threshold on a criterion index.”	We decided to cut out this method
Page 4, Figure 2(A): I believe that this figure is not mentioned in the text.	Corrected, we will mention it in the page 2
Page 4, lines 3-4: I think this sentence should be moved to the section 6.2 as it motivates the choice of the benchmarking method.	We will move this sentence to the comparison methods section and modify it according the new structure of paper.
Page 5, line 7: “the areal difference asymmetry index by Knighton” has not been mentioned before, the authors might consider adding more context to this statement.	It was felt that there is no need to define this method because it’s just an example of methods existing in the literature. However, we will add it in the table that summarizes all the previous methods and techniques.
Page 5, line 32: the manuscript states: “a common geomorphological and hydrological” methods, I suggest specifying these methods.	We will change the entire sentence according to the new structure of the paper
Page 6, line 8: was the channel width/channel bankfull width used to compute dimensionless values of wavelength? I think this sentence is not clear.	Yes, it’s not clear. Here we are talking about the dimensionless pool spacing, in which there are researchers who use the definition $\boldsymbol{\lambda}^* = \frac{\boldsymbol{\lambda}}{\boldsymbol{W}}$ (mean channel width) while others use $\boldsymbol{\lambda}^* = \frac{\boldsymbol{\lambda}}{\boldsymbol{W_{bf}}}$ (mean bankfull channel width). We will change it in the revised version.
Page 6, line 9: what do the authors mean with	“certainty of these ratios” means their efficiencies

"certainty"?	to give more consistent results, so we will change it to "efficiency"
Page 6, line 14: I suggest avoiding colloquial expressions such as "a great deal".	We changed it to: "Some researches have investigated"
Page 6, line 32: I suggest rephrasing this sentence and avoid the use of "we".	We will change all the sentence to: "These reaches contains mainly pool-riffle morphologies, they have slopes …"
Page 7, line 5: I believe that information on slope has been previously provided in page 6, line 32. Could please the authors explain the added value of this sentence?	This line has been added to define the thalweg elevation and how it can be estimated. That's why we will delete it and add this information in the lines 1 and 2 p7: "they have slopes between 0.002 and 0.013 m.m^{-1} (estimated from the talweg elevation which is the lowest point in the section)…"
Page 8, line 11: please clarify the sentence "It is based on interpolations rather than extrapolations".	As said before, the role of the 1D hydraulic model (Fluvia) was simply to generate water surface profiles for discharge values other than the surveyed ones (i.e., interpolate the rating curves between values of surveyed discharges, and extrapolate slightly above highest surveyed discharge). In our revised paper, we will solely rely on measurements at the lowest surveyed discharge and use the model to provide estimates of Manning coefficient n, we will use these values in order to compute the third degree of freedom, bed shear stress $\tau_b(x)$, along the reach. So this part form line 10 to line 14 will be modified by an explicit description of the model and the data set.
Page 8, line 13: "visually": do the authors mean that they performed a manual calibration of the hydraulic model?	It is a typo, we checked the calibration visually, but we adjusted it with a minimization function.
Page 8, line 14: please remove the second full stop.	Corrected.
Page 8, line 14: "multi-section flows": do the authors mean that the numerical model is used to predict a number of quantities (e.g. the elevation of the water surface, wetted perimeter, wetted surface,: : :) at a number of cross sections?	The use of the numerical model (Fluvia) will be simply to generate calibrated estimates of Manning coefficient n that we will use to compute the bed shear stress $\tau_b(x)$ along the reach. For the other cross-section variables, we will use only measurements at the lowest surveyed discharge.
Page 8, line 3: why is the minimum discharge used for the implementation of the method?	We chose the minimum discharge (low flow) in the development of the method because it is the discharge through which we can visualize the variability of the bathymetry (alternating morphological units).
Page 8, line 6: does "it" stand for "relevant information"? The authors might consider editing the structure of this sentence.	This section will be removed from this paper as suggested by the second reviewer Prof. Gregory Pasternack.
Page 8, line 8: I believe that "the trend" has not	The only detrended variable was bed elevation: we

been explained before. I suggest clarifying this sentence. What does "detrended variables" mean? How are these variables computed?	computed a series of bed elevation anomalies $\varepsilon_z(x)$ such that: $z_{bed}(x) = -S_{bed}\, x + b + \varepsilon_z(x)$, where S_{bed} is the mean slope of the reach and $\varepsilon_z(x)$ has zero mean. This part is not necessary anymore.
Page 8, line 13: "contain the most explained variances" do the authors mean that those directions can explain the variability of the data? I suggest clarifying this sentence.	The PCA analysis will be completely removed so this discussion is not relevant anymore.
Page 8, lines 18-20: does these results confirm/contradict previous studies?	The PCA analysis will be completely removed so this discussion is not relevant anymore.
Page 9, figure 4: could please the authors explain the meaning of Dimension 1: : :9?	The PCA analysis will be completely removed so this discussion is not relevant anymore.
Page 9, lines 5-6: I think this sentence is unclear. What is the relationship between bed elevation and hydraulic radius? The statement seems to be contradictory. Moreover, I was wondering whether any correlation between bed elevation and hydraulic radius is meaningful. Bed elevation is a geometric characteristic at the point scale. The hydraulic radius depends on discharge, river bed slope, cross section area.	Here we are not talking about the physical meaning of these variables but their variability. The hydraulic radius is the cross-sectional area divided by the wetted perimeter, so the hydraulic radius, the cross-sectional area, and the depth are positively correlated, while the water surface elevation is the depth plus the bed elevation, so the depth and the bed elevation are negatively correlated. So the bed elevation and the hydraulic radius are negatively correlated. It's just trivial findings. For that we will choose in the revised paper variables that are not dependent.
Page 9, lines 6-8: the explanation based on hydraulic radius and Froude number is reasonable and (almost) intuitive. I suggest to clarify the added value of this finding compared to the existing literature.	There is no added value of this finding, we were wrong about the justification of our choice of variables. We will change all this section as we mentioned it before.
Page 9, line 9: I suggest clarifying the importance of bed elevation.	Historically, bed elevation has been seen as the most relevant variable in order to characterize geometric and flow variability. Since water surface elevation cannot change in space as fast as bed elevation, local bed elevation (and slope) is an important driver of depth and velocity variations along the reach. However, width variations have been found to be important as well, so a multivariate approach must clearly be favored.
Page 9, line 10: what do the authors mean with "we smooth" the data?	The formulation was wrong; in fact the processing mentioned in this sentence was only applied to bed elevation: since the trend of bed elevation is not necessarily linear, we performed a more general removal of very low frequency components (wavelength larger than 7 times the mean bankfull width) before applying thresholds. Since we will not use bed elevation anymore, this processing is no longer relevant (and it was not a smoothing anyway).

Page 12, lines 11-13: I suggest improving the readability of this sentence.	We will change all the structure of this paragraph
Page 12, lines 16-18: please improve the structure of this sentence: “have been interested: : :but working”, both the verbs have the same subject.	We delete this sentence in the revised paper.
Page 12, line 18: “analysis” is repeated.	Corrected.
Page 14, line 12: I suggest replacing “evacuate” with something more appropriate (an option could be “remove”).	Corrected.
Page 15, line 3: please clarify “It also represents” (what does “it” stand for?)	“it” stands for “the curve that continuously crosses the domain” and also “K(x)”. We will replace it by “This curve K(x) also represents …”
Page 15, line 11: could please the authors better explain why this correction is applied?	Equation (21) actually gives the amplitude of the pseudo-periodic signal through inverse wavelet transform. In this reverse transformation we need to multiply by $\sqrt{\boldsymbol{s}} = \sqrt{\frac{\mathbf{1}}{\alpha K(x)}}$ where $\boldsymbol{\alpha}$ is the Fourier factor (Torrence and Compo, 1998), since we multiply by $\sqrt{\frac{\mathbf{1}}{s}} = \sqrt{\boldsymbol{\alpha K(x)}}$ in the direct transformation (Equation 14).
Page 15, line 15: please correct the structure of this sentence: “we limit the study only with univariate analysis”. Moreover, could please the authors justify this choice?	As we said before, we will focus in the revised version of this paper on both the univariate and the multivariate analysis and we will compare their results with the BDT (O’Neill and Abrahams, 1984).
Page 15, line 26: please clarify the meaning of “multivariate case”.	The multivariate case is the extension of the univariate to a set of N real-valued signals; it is described in Lilly and Olhede (2009). We will describe this case and develop its transformations in our revised version.
Page 17, Table 3: Table 3 and Table 2 show the results of the two methods for the same river reach. The authors might consider displaying these tables in the same page in order to allow a straightforward comparison of the results.	In the revised version we will cut out these kind of results.
Page 18, lines 2-4: I think that this sentence is unclear.	We will replace it with a clear sentence according to the new results that we will have.
Page 19, line 3: I believe that these results demonstrate a good level of agreement between the two methods. In my opinion, these results do not provide explicit information on the accuracy of the methods.	Yes, these results do not prove the accuracy of the methods. For that, we chose presenting one method (wavelet method) and discuss it with one benchmark methods as explained before.
Page 19, line 5: the BDT methods is used to “validate” the results of the proposed methodologies. This choice implies that the BDT method is more accurate than the new methods	In this study, we consider the BDT method as a benchmark method. We do not consider a specific method to be the “true” or “reference” one, we only apply several methods to have a general idea

introduced in this manuscript. Is this correct? If so, what are the benefits/ advantages of using the two proposed techniques?	on the uncertainties in the identification of morphological units.
Page 19, lines 19-20: please clarify this sentence.	We will delete this sentence in the revised version.
Page 19, line 23: the manuscript states that the results of BDT "are closer to the other methods and to reality". I strongly recommend to better substantiating this sentence. Which are the "other methods"? What does "reality" mean? Was the BDT method compared with field data? In which case study?	True, This sentence is not clear, we will delete it.
Page 20, lines 3-4: could please the authors clarify this sentence?	We will change all the discussion according to the results that we will have.
Page 20, lines 6-7: please rephrase this sentence.	This sentence is not clear, we will change it in the revised version.
Page 21, line 2: a Froude number of 0.30 looks a bit large. Could please the authors explain this result?	We will dismiss the Froude number In the revised version. But for example in the study of Jowett (1993) and Clifford et al. (2006), they found values close to 0.3, so we think that these values are a bit large but acceptable. Jowett—Pool, run, and riffle habitat 243  **Fig. 1** Kernel density functions of velocity/depth ratio, Froude number, and water surface slope in pool, run, and riffle habitats.
Page 21, line 3: it seems that the average values are driven by the results of the Graulade river, Are the average values representative of the sample?	If we exclude the Graulade river we will find and average of 0.20 for the index and 0.17 for the wavelet method. These results are nearly close the 0.23 and 0.20.
Page 21, line 10-17: these lines present a comparison between the results of this study and some of the previous studies. The authors might (or might not) consider using a table to summarise these comparisons.	This is a good idea.
Page 21, line 21: I suggest motivating this sentence. Why aren't the previous methods considered quantitative?	We will delete all this sentence
Page 22, line 1: is "crossing" the most appropriate word?	We will delete all these sentences
Page 22, line 3: please clarify this sentence	We will change this sentence in the revised version

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Reply to Prof. Gregory Pasternack

Dear Prof. Gregory Pasternack,

We thank you for your comments, which will help improve the clarity of the manuscript as well as the choice of the methods.

According to both reviews we decided to make very substantial changes to the paper. This work is a methodological study that introduces relatively new wavelet analysis tools in the field of geomorphic analysis (namely, Wavelet Ridge Extraction), in order to identify the pseudo-periodicity of alternating morphological units from a general point of view (and not only pool-riffle morphology). We did initially introduce an index method as a benchmark, but this index was poorly designed due to a lack of physical basis for the choice of the variables. We also neglected some relevant literature on the identification of the morphological units using DEMs, which could be used as benchmark methods in this paper.

For that, we suggest changing the title of this paper to "***Automatic identification of alternating morphological units in river channel using wavelet analysis and ridge extraction***". This will be more general and focuses on the method and not on the pool-riffle morphology.

We have presented two methods in this article. The first one is the wavelet method which represents alternating morphological units (pools and riffles) as pseudo-periodic signals with a continuous wavenumber function K(x). The other one is the index method which is a benchmark method that gives a discrete identification of the morphological units.

According to your suggestions, we will cut out the index method. We will focus only on the wavelet analysis and ridge extraction in the univariate and the multivariate cases and compare its results with the benchmark method: BDT (O'Neill and Abrahams, 1984) to the bed elevation data. We didn't compare it with other recent methods (e.g. Hauer et al., 2009; Wyrick et al., 2014) because they require thresholds (expert judgment) collected from the field, which is not possible in our case.

We will also minimize the use of modeled variables and apply the methods directly on field measurements (velocity, hydraulic radius variables at the lowest surveyed water level and planform curvature angle). We will use modeling results (Fluvia model) for bed shear stress only, as the energy slope cannot be determined in a sufficiently accurate manner with the measurements.

For the literature, we missed many recent studies and methods in relation to this work. So first we will add a table that summarizes examples of methods of identifying these morphologies and the variables chosen to do that. Second, we will change and add many recent works especially those working with meter-resolution digital elevation models (DEMs). Finally, we will clearly state the objectives of this study in the abstract and in the introduction.

Another important thing is that we propose a new structure of the paper:

I- **Introduction**:

First, we will state the scope of this study with adding more fields of its application. Second, we will introduce a literature review of metrics, variables used to identify and characterize the alternating morphological units. We will focus on two kinds of numerical criteria computed at reach scale:

- The distribution of spacings between morphological units (mean, mode, etc.),
- After computing the mean values of geometrical and flow properties (velocity, hydraulic radius, bed shear stress, etc.) in each class of morphological units (e.g. pools, riffles, runs, etc.) we will evaluate the covariance matrix of these parameters.

1) **State of art methods for a quantitative assessment of morphological variability within a reach**:

We will present some recent methods and works in the identification of these alternating morphological units (pool-riffle in our case) and state their objectives and limitations. We will start with the Bedform Differencing Technique (BDT, O'Neill and Abrahams, 1984), which is simple but uses bed elevation as the sole variable, and relies on a tolerance criterion on elevation differences. We will then review index methods like Mesohabitat Evaluation Model (MEM, Hauer et al., 2009) which classify each position in the reach into a given discrete morphological unit (pool, riffle, run, plane bed, etc.). These methods rely on expert judgement to define the thresholds that define parameter classes. Finally, geostatistical methods (e.g. Legleiter, 2014) give a continuous description of river channel properties in spatially stationary way, using longitudinal and transverse variography. For these reasons, we are searching for a method that gives a continuous description of geometrical and flow characteristics along the reach with a non-stationary description.

2) **Study objectives**

We will state that this work aims to introduce relatively new wavelet analysis tools in the field of geomorphic analysis, the Wavelet Ridge Extraction, in order to identify the pseudo-periodicity of alternating bedforms from a general point of view. In this study we will use a dataset that presents mainly pool-riffle morphologies, but the method can be applied to any morphology.

We will present the scheme of the paper which include a methodological section of the wavelet analysis and ridge extraction in the univariate and the multivariate cases, a section that presents the comparison between our method and the BDT, a discussion section, and conclusions.

II- **Data set and study reaches**:

We will present the six reaches, more explicit information about data collection, planform curvature angle computing and about the numerical modeling (Fluvia).

III- Wavelet method

1) Wavelet analysis and ridge extraction:

We will present a general introduction about wavelets including some methods such as the Wavelet Transform Modulus Maximum (WTMM, Gangodagamage et al., 2007) and other studies using the wavelets in the geomorphological field (Lashermes et al., 2007; McKean et al., 2009). Procedures such as the WTMM (Muzy et al., 1993) consist in extracting components of the signal, but they are not specifically designed to identify pseudo-periodic components in a univariate, let alone in a multivariate case. For this reason, we introduce the procedure called Wavelet Ridge Extraction (Lilly and Olhede, 2009).

2) Univariate case

We will present the methodology of this method in the univariate case using one of the four variables (velocity, hydraulic radius, bed shear stress, and planform curvature angle).

3) Multivariate case

We will present the methodology of this method in the multivariate case using the four variables (velocity, hydraulic radius, bed shear stress, and planform curvature angle).

IV- Results

1) Univariate vs Multivariate:

We will compare the univariate with the multivariate results with computing some statistics. And we will use the multivariate wavelength to model the bed elevation of the reaches without using it as a variable.

2) Comparison with the benchmark method

We will compare our method’s results in the multivariate case with the selected benchmark method from the literature: BDT.

V- Discussion

We will discuss results (longitudinal spacing, number of morphological units, etc.) with literature and with the benchmark method.

VI- Conclusions

Kind regards,

The authors

Comments:

It is unfortunate that the manuscript does not have continuous line numbering to aid reviewers and editors with referring to locations easily, even the repeating page numbers are only every 5th value, which is not convenient. Actually, based on page 8 where there is new numbering at the onset of section 4, I am totally confused as to how line numbering is done and it makes it harder to review the paper in a discussion format that requires me to write out all my comments rather than simply mark up a manuscript. In future manuscripts, always include full and continuous line numbering.

Response:

We used the Latex Template; maybe there is a problem in the numbering characteristics that we will modify in the revised version.

First 2 paragraphs of the introduction. It seems odd to me that the main reason why anyone should be interested in understanding the sub-reach variability of river topography is because of the potential application of such information to flood forecast modeling. Even in the applied realm that is only 1 of many applications that could be referred to. In my own research, the primary motivations are that such data is required for river design for a wide variety of purposes including river rehabilitation and enhancement and also because it informs fluvial ecohydraulics. In light of systemic global ecological collapse, these are more important to society than flood forecasting, in my professional opinion. At a minimum, I think the authors should identify a few more reasons why knowing topographic variability matters and add a citation for each. Also, of course, geomorphologists want to understand it in its own right as a basic scientific question that requires no justification, and of course it is also the case that this variability controls fluvial processes, so the lack of knowledge about it means that we really know little about processes; less than I think most people realize.

Response:

It's true that there are more reasons why knowing topographic variability matters like you mentioned above. For that we will modify the first paragraph of the introduction by adding examples of application of our study like the design of a synthetic river topography which is implemented in river restoration (e.g., Wheaton et al., 2004a), habitat modeling, ecohydraulics (e.g., Pasternack and Brown, 2013), and of environmental modelling (oxygen exchange, fish habitat) and also that this variability controls fluvial processes as sediment transport, but not focusing only on flood forecasting.

P. 2, lines 3-8. While this is generally true, the authors seem to be unaware that my lab group has already published theory and code that is the first to procedurally generate river terrains exactly to specification from the equations and parameters, and this methodology does include sub-reach-scale variability that can go to as high of a frequency as one wants to make it, so quite small scale. There is always more to do, but I think this is relevant to the claim of this paragraph. I see that this paragraph has 4 citations for the first sentence alone, which seems like too many, so removing 1-2 of those could make way for citing this relevant work if the authors agree that what we published does in fact do what they say is an important thing to do, even if not perfectly, but still more than anyone else thus far. The journal citation is Brown, R.

A., Pasternack, G. B., Wallender, W. W. 2014. Synthetic river valleys: creating prescribed topography for form-process inquiry and river rehabilitation design. Geomorphology 214: 40-55. 10.1016/j.geomorph.2014.02.025. The code is open-source and free to the world presently coded in R as "River Builder". The R package and user's manual can be downloaded from the CRAN website at https://cran.rproject.org/package=RiverBuilder. The code also includes the Perlin function that can create very small scale features, and that is a common method for generating landscape terrains in the video game and animation industries. In the future we hope to add the capability to parametrize the sub-reach-scale fluctuations in spatial series of detrended bed elevation and lateral topographic breaklines using wavelet parameterization.

Response:

This is true; we shouldn't ignore these studies because they are relevant and important to this literature. For that we will change the paragraph in the page 2 from the line 3 to 8 by: "Many researchers are working on determining the best simplified representation of channel geometry (Saleh et al., 2013; Grimaldi et al., 2018), based on the variability of cross sections but without the knowledge of the bed elevation variability or the river sinuosity. While other studies focused on the generating of river channels with taking into account the sub-reach scale variability using geostatistics and variogram tools (Legleiter, 2014a, 2014b) or a geometric framework modeling with geomorphic covariance structures (Brown et al., 2014). Longitudinal variability in river geometry has greater impact on the simulation of the water level than the cross-sectional shapes (Saleh et al., 2013) and it must be taken into account in the hydraulic models."

The third paragraph of the introduction serves no required purpose and neither does Figure 1. Both can be deleted with no loss of understanding. Yes, rivers come in different types, but the main thing readers need to know is that this is a study of riffle-pool reaches and that the method can apply to other reaches; these ideas can be promoted without any of this paragraph, as is indicated by the first sentence of the very next paragraph just fine.

Response:

It's true; we should focus on the alternating morphological units especially the riffle-pool sequences without including this paragraph and the figure 1. We will add to the line 14: "This topographic variability is related to the channel morphology types. In this study, we focus mainly on alternating alluvial channels especially pool-riffle sequences, even though the method presented here could be used to analyze any alternate morphological units (MUs).", and we will remove lines from 9 to 13 and figure 1.

p.2, lines 15-16. The objective of what? The writing is unclear here. I disagree that the main purpose of quantitative analysis of channel topography is just to get pool spacing. In support of our River Builder software, one normally wants to analyze many aspects of reach-scale topographic variability so that they can all be parameterized and used to make realistic synthetic rivers. Other important variables would be parameterizations of thalweg planform curvature, base flow and bankfull channel width undulations, floodplain width undulations, and then how all of these are phased relative to each other (in time series *that's "coherence" and "cross-phase"). Thus, pool spacing is certainly one useful data output, but not alone or necessarily most important.*

Response:

This is true, the paper isn't about the pool spacing identification, but its purpose is for example extracting some quantitative properties of these alternating morphological units such as the mean and the mode of their longitudinal spacings, with a "continuous" vision of the topography instead of a discrete classification. This will be done by focusing on two kinds of numerical criteria computed at reach scale: The distribution of spacings between morphological units (mean, mode, etc.), and after computing the mean values of geometrical and flow properties (velocity, hydraulic radius, bed shear stress, planform curvature angle, etc.) in each class of morphological units (e.g. pools, riffles, runs, etc.) the evaluation of the covariance matrix of these parameters.

I also note that tat the authors never use their reach site results to present any conclusions about the science of pool spacing, so if it is so important than its value should be evident in how the results are used to advance science.

Response:

We should be clear in that point that our paper is methodological research that propose a new method with new developments. Of course we will add some conclusions about the longitudinal spacing results and the covariance between the chosen variables.

p. 3, lines 1-4. No need to define wbf twice. Remove one of them.

Response:

We will remove the second one and change the first at line 3 by: "the reach average bankfull width (wbf)".

p. 3, lines 7-17. A major problem with the historic work cited here that its all pre-2001 and how it is presented is that the authors are not addressing the equal importance of channel width undulation to channel depth undulation. Richards in the 1970s understood it and wrote about the importance of width. However, because people didn't tend to make width profiles down rivers, the focus wrongly got limited to depth undulation in the literature of the late 20th century. Of course, authors studying velocity reversal concepts did start to understand this problem pretty well by 1990. With modern high resolution DEMs since 2000, that problem is over and now we are in the era of looking at how depth and width co-vary to control pool and riffle topography and morphodynamics vis-a-vis the "flow convergence routing" mechanism explained by MacWilliams et al (WRR, 2006) and explored further by Prof. Jose Rodriguez in recent WRR papers as well by my lab group in several articles (Sawyer et al., Geomorph., 2010; Brown et al., Env. Man., 2015; Strom et al, Hyd. Proc., 2016; etc). My lab group has published a series of papers on the importance of linked depth and width undulations that has culminated in a new sub-reach scale channel unit classification relevant to this paragraph and this study. See these two articles, the rest leading up to these are cited in them: -Pasternack, G. B., Baig, D., Webber, M., Brown, R. 2018.

Hierarchically nested river landform sequences. Part 1: Theory. Earth Surface Processes and Landforms. DOI: 10.1002/esp.4411. -Pasternack, G. B., Baig, D., Webber, M., Brown, R. 2018. Hierarchically nested river landform sequences. Part 2: Bankfull channel morphodynamics governed by valley nesting structure. Earth Surface Processes and Landforms. DOI: 10.1002/esp.4410.

Response:

You're right, we didn't present our literature in that chronological way, which is interesting for the reader, we should focus not only on the identification methods but also on the science of alternating bedforms including pool-riffle, but honestly a methodological paper focusing on alternating bedforms should mention these works and shouldn't neglect any of them. As you suggested, we will change this entire paragraph and summarize it in a table and add studies done after 2000. In addition to that we will present the literature of depth and width undulations in relation to pool-riffle, the same thing for the modern high resolution DEMs, and the thresholds chosen in literature which would help us to discuss our results.

p. 3, lines 20-26. Yes, I agree with all of this, though I don't think wavelet analysis cannot be called "new" as it has been published in geo/hydro journals for decades now; what's new is high quality topo data to apply it to, though that is present intros study. I'm surprised by the citations the authors offer here, as they are not very relevant compared to other options, such as (most importantly) Gangodagamage et al. (Geomorph., 2007) but also Lashermes et al. (WRR, 2007) and McKean et al. (Rem. Sens., 2009). One can use spatially evolutive Fourier analysis and autocorrelation analysis or, if one limits the analysis to a single reach, regular Fourier analysis where the average parameterizations are reasonable.

Response:

What is new is the method presented itself and the identification of alternated morphologies, since it is never made with wavelets. But for the wavelets, yes it has been present for decades, however it is still less used compared to Fourier. Wavelet Transform Modulus Maximum (WTMM, Muzy et al., 1993; Gangodagamage et al., 2007) and other studies using the wavelets in the geomorphological field (Lashermes et al., 2007; McKean et al., 2009) consist in extracting components of the signal, but they are not specifically designed to identify pseudo-periodic components in a univariate, let alone in a multivariate case. For this reason, we introduce the procedure called Wavelet Ridge Extraction (Lilly and Olhede, 2009). These works will be presented in the revised version.

One might even argue that the locations where the Wavelet analysis indicates a change in parameters could be a reach break. Certainly wavelet analysis is a very good way to go for this to objectively delineate reach breaks, but preferably with a multivariate strategy using both depth and width variables. A good comparison would be to look at the riffle-pool quasi periodicity analyses of Brown, R. A., Pasternack, G. B. 2017. Bed and width oscillations form coherent patterns in a partially confined, regulated gravel–cobble-bedded river adjusting to anthropogenic disturbances, Earth Surface Dynamics, 5, 1-20, doi:10.5194/esurf-5-1-2017.

Response:

That’s what we will do in the revised version, we will focus only on the wavelet analysis and ridge extraction in the univariate case using one of the four variables (velocity, hydraulic radius, bed shear stress, and planform curvature angle) and the multivariate case by using the all four of them and compare its results with the benchmark method: BDT.

P.15, line 14. This sentence makes a key determination that flies against the same kind of decision-making applied to the index method of section 4. Specifically, the determination of riffles and pools is going to rely entirely on bed elevation. It seems odd that scientists who begin with the conjecture that multiple variables should be used to determine riffles and pools would now contradict themselves and only consider one variable. My view of it is that both decisions are arbitrary, as (a) the former was based on a questionably PCA analysis lacking a mechanistic basis and choosing interdependent variables rather than the proper independent ones and (b) the latter is likely based on the amount of work it takes to apply the wavelet methodology and so its application is being limited to only one variables and to only 1 reach instead of all the reaches. I am making my own guess with (b), but the authors provide no justification for limiting the analysis to only 1 reach after introducing so many reaches. Similarly why not do all three variables the authors deem important. A quick check of the scientific literature confirms that multivariate wavelet analysis exists and is available for use. And then there is the issue of how the variables couple to affect riffle and pool occurrence, structure, and resultant processes. The decision-making here is too opaque and needs explanation per these issues. I expect the decisions cannot be justified, but the authors deserve a chance to try.

Response:

According to these comments:

(a) We totally agree with you that the choice of these 3 variables is unsound, so we will keep the multivariate case with a physical combination of variables. In the revised version, we will focus on the wavelet analysis using the univariate and the multivariate with four variables; we choose the classic three ones: velocity, hydraulic radius, and shear stress, in addition to the planform curvature angle that represent the planform variability.

(b) For the multivariate case, it isn’t a problem of computation time, we already have an implementation of the wavelet ridge extraction in a multivariate case; however, we initially chose not to present it in the paper because we need to introduce a specific criterion to identify the local wavenumber K(x). Basically, in the univariate case, wavelet ridge points are those points of the (x,K) plane where the phase of the wavelet $\phi(x,K)$ changes in space exactly at rate K (i.e., $(\partial\phi/\partial x) - K = 0$: the signal is locally similar to a sinusoid of wavenumber K in rad/s). In the multivariate case, we search not for an equality but for a local ***minimization of the norm of the vector*** $[(\partial\phi1/\partial x) - K ; (\partial\phi2/\partial x) - K ; (\partial\phi3/\partial x) - K]$ with respect to K : the local wavenumber K(x) is such that ***all four variables locally look like sinusoids of same wavenumber K(x), but with potentially different phase shifts***. Clearly, this co-evolution is needed to identify morphological units. We will add the necessary mathematical developments in the appendix of the revised paper.

p.5, lines 19-20. This explanation is incorrect on two levels. First, energy gradient is more than just water surface slope, because energy also accounts for the velocity head that is not in that term. Often velocity isn't changing over long distances or is assumed to not change, but along a riffle crest and in the transition to a pool it definitely changes quite a bit, so strictly speaking one has to account for that. Second, the energy gradient is stage dependent, because the steepest gradient is always associated with the vicinity of the smallest cross-sectional area, all other things being equal.

Response:

The complete quotation of the paper by Yang (1971, p. 1567) reads: "For practical purposes, the energy gradient for most natural streams may be replaced by water surface slope without much error". So we are of course fully aware of the difference mentioned in the referee's comment, even though this difference between energy slope and water surface slope is usually small for "low Froude" rivers such as the ones studied here. But to avoid this misunderstanding we will refer only to the energy gradient.

At low discharge the way the authors describe it is true, because at low discharge riffles have the smallest XS area. However, once the discharge exceeds the value for the minimum cross-sectional area of the reach to be elsewhere, then it is not at the riffle any more. At some high flow it will become at the pool location, and of course this is the main reason why pools scour and riffles aggrade to maintain relief in alluvial channels, all other things being equal (especially substrate). This stage dependence is a key issue to account for in any scheme to evaluate where riffles and pools are located and it its why considering only depth and ignoring width has always been a mistake by the river science community. Now that we have width data commensurate to depth data, we can move on to the proper treatment of the problem considering their linked co-variance.

p.9, lines 7-8. These claims apply only to low discharges, due to the flow-dependent nature of riffle-pool hydraulics. How they develop as discharge increases depends on the shape of the cross-sections (especially depth vs width "geomorphic covariance", per flow convergence routing theory.

Response:

Absolutely true, that is why we chose low flow instead of high discharges. We completely agree that the maximum shear stress may be located in different morphological units at high discharges than at low discharges, and that it is very important to understand how relief is maintained. Exploring this near-bankfull behaviour is the reason why hydraulic modeling was needed in the first place in the study by Navratil et al. (2006), since it is difficult to obtain field measurements precisely at bankfull conditions. The wavelet ridge extraction could perfectly be applied at bankfull conditions, but since it would rely on modeling results if we want to perform it on our dataset, we will leave it out of the scope of the paper.

p. 5, lines 22-37. All of these methods retain the limiting viewpoint that they put a primacy on riffles and pools, either ignoring other morphological units (MUs) or treating them as irrelevant. Thankfully, 2D and 3D hydrodynamic modeling ends that mistake and enables objective mapping of all MUs with decision-tree analysis. This approach was explained by Wyrick et al. (Geomorph, 2014) and then applied in Wyrick and Pasternack (Geomorph., 2014) to not only show the greater diversity of MUs beyond riffles and *pools, but also to compute simple metrics like pool spacing. Thus, Wyrick and Pasternack (Geomorph., 2014) presented a novel methodology to extract pool spacing from 2D hydrodynamic model outputs of MUs using GIS tools. That is very relevant to this literature review, because it shows recent progress in automated extraction of this metric. The authors are arguing that their methods are more automated and better than pre-existing methods, but they have not actually considered more recent automated methods.*

Response:

This study of Wyrick et al. (2014) is relevant and presents a method that should be mentioned in the literature of this paper and also should be discussed in the discussion part.

Meanwhile, the sentences about the outstanding work by Almeida and Rodriguez as well as Parker goes off topic from pool spacing to get into the separate topic of riffle-pool morphodynamics, of which there is a very long and illustrious literature not addressed. Best to cut those at this location and stay focused on the directly relevant literature about pool spacing that is the focus of this study. They may be relevant if the revised manuscript ever addresses processes explicitly.

Response:

True, we should focus only on alternating morphological units and all references linked to morphodynamics or pool-riffle processes should be cut out from the paper.

p.6., lines 5-27. Very good literature review and written well, just not accounting for many recent studies since 2001.

Response:

We will add more recent studies.

p. 7, line 6. The sentence about having surveyed "many" cross-sections is poorly constructed and, in my view, not accurate. Terms like "many" are relative, so it could be that for one person any arbitrarily small number of cross-sections would still seem like many; that makes it hard to argue the point. However, the key metric here is that one cannot analyze for topographically significant spatial frequencies at resolutions smaller than the minimum XS spacing, and that's already quite conservative. For that reason, my lab group uses vastly denser cross-sectional spacing than that used here. For example, in Pasternack et al. (ESPL, 2018b) we used a spacing of 3% of bankfull width. That's "many". For another group, Legleiter (Geomorph., 2014b) spaced a XS every quarter channel width. In contrast, in this study, an analysis of Table 1 finds that cross-sections are spaced between 0.46 to 2.9 times bankfull width, with two reaches not even having 1 XS every bankfull width. These numbers of cross-sections are more like the amount used in a conventional reach survey to obtain reach-average depth and width metrics, not to identify the underlying nature of variability. I think if the authors refer to previously cited articles above about spatial series analysis of rivers topography plus Legleiter, they'll get a better sense of what is needed to get at the detailed patterns of fluvial topo spatial series at the sub-reach scale. This issue *doesn't invalidate the study, but just recommends to back off the "many" and get to saying "a normal number of cross-sections typical for a 1D hydraulic modeling study" or something like that.*

Response:

We agree with you in that point, the use of "many" in this sentence is relative, so we will change it to "Cross-sections were surveyed".

Also, these cited works could be referred to in the discussion section to help compare and contrast undulation metrics from different studies, including when undulations may not have high enough amplitude to become a "riffle" or "pool" but are still big enough to make a difference for the intermediate morphological units that are mentioned but not investigated in this study.

Response:

We will cite these works in the literature review and we will discuss our work according to it to make some conclusions on the parts where we have pools and riffles without investigating the other MUs and also about longitudinal spacings.

p. 7, line 6. I think a bigger questionmark for the technical soundness has to do with the mindful decision to not have all cross-sections regularly spaced, but to place them primarily at hydraulic controls and morphological breaks. The authors then interpolate to get a grid, but the source data is not uniform. I fully understand why that would be done for a 1D hydraulic modeling study and given perhaps limited resources and no lidar data, but there is no question whatsoever that biased (aka mindful) XS placement impairs and calls into question spatial series analysis as far as objective identification of parameters. By placing the XS where the authors think important hydraulic and morphological things are happening, then necessarily the wavelet analysis and any other method is also forced to bias results toward the same outcome of where significant things are happening. On the other hand, when I put an XS every 3% of bankfull width along the series, then there is no chance anything will be missed and the algorithm can decide for itself what the frequencies, amplitudes, and phases (and other parameters) are for that reach. Equal spacing of XS is the best approach for unbiased results. I think there are some things that can still be analyzed with a small number of mindfully selected XS positions, but I would never take this approach. I do understand the lack of availability of lidar and other remote sensing data to facilitate high-resolution mapping though, but then one has to be thoughtful about what one can reasonably achieve. I think the way forward would be for the authors to explain their viewpoint on why they have a sufficient number of XS for the goals of their study in comparison to the highest density used by the references cited above.

Response:

We fully agree that the larger the number of cross-sections, the more robust identified correlations will be. Unfortunately, we had to use the dataset as it is as we have currently no means of doing additional field work to enrich it. But we do not think that the "biased" placement impairs the overall methodology. Of course we would be pleased to have the opportunity to test this approach on a much denser dataset in the future.

p. 8, section 4, line 1. "Hydrological" should be "hydraulic". I believe. These are not interchangeable. Hydrologic would be rainfall-runoff and water balance related, could be purely discharge but discharge alone does not identify riffles vs pools. Hydraulic means on the basis of the depths, velocities, and other flow kinematics.

Response:

Indeed the correct term is clearly hydraulic in this context.

p. 8, lines 8-16. I am confused by the writing. On line 8 it says hydraulic data were "surveyed" at 3 discharges. Please clarify that the data were measured in the field and then it is necessary to also describe how the data were measured. There are many different methods possible and one cannot undertake analyses of data without stating how it was collected. Moving on from there, if the data was actually measured, then I have absolutely no idea why the authors mention a method involving 1D hydraulic modeling of the sites. Given field observed cross-sections and hydraulic data, once could use a pure XS analyzer like the old, free software WinXSPro and many other GUIs to extract geometric variables like hydraulic radius with no numerical modeling. If the derivative variables like Rh and Fr are not based on field data, but instead are coming from a 1D hydraulic model, then it opens up a whole can of worms regarding the accuracy of the model outputs, which then necessitates an explanation of model calibration and validation performance. All of this is written unclearly and needs to be revised to explain to readers what is going on. This has profound consequences for evaluating the study.

Response:

Data are measured in the field; we will add a description of how it was collected from Navratil et al. (2006): "Cross-sections and water surface profile measurements were surveyed in 2002 – 2004 covering the main channel and floodplain and using an electronic, digital, total-station theodolite. Water surface profiles were measured at different flow discharges."

Reach	Number of cross-sections	Flow discharge surveyed (m3/s)	Gradient
1	14	0.22 and 1.26	0.0125
2	32	1.85 and 2.41	0.0044
3	21	0.18, 1.13, 1.72, and 1.99	0.0018
4	26	0.19, 0.33, 0.8, and 11.5	0.0024
5	25	0.15	0.0060
6	36	0.21	0.0047

The numerical model used in this study aims to calibrate the Manning coefficient in order to fit the surveyed water surface profiles. In our revised paper, we will solely rely on measurements at the lowest surveyed discharge and use the model to provide estimates of Manning coefficient n, we will use these values in order to compute the third degree of freedom, bed shear stress $\tau_b(x)$, along the reach.

Section 4. In the previous section it was stated that hydraulic variables were "surveyed" at 2 low discharges and 1 near bankful discharge. As the relative magnitudes of the variables between rifles and pools are stage dependent, it matters which flow was used to for the analysis in this section. The authors should state that. If somehow all three discharges were used, clarify how. In fact, at-a-station hydraulic geometry is an important tool for identifying riffles and pools more holistically considering the totality of the bankfull channel, so it is too bad few people take note of that and apply it to this purpose.

Response:

We mentioned in the page 8 at line 3 that we worked with the minimum discharge Q_{min}.

p. 8, section 4, lines 4-5. Most people use PCA for challenging multivariate problems with complex interrelationships that are unknown and thus this is the first way to get a sense of how variables interrelate. That does not characterize the situation for riffle-pool geometry and open channel hydraulics. A wiser strategy here could be to use Buckingham Pi theorem dimensional analysis to create the variables of interest. Also, one can easily reason out that really the variables that matter are those that control or respond directly to morphodynamic processes, such as flow convergence routing or meander migration. That can then guide wise variable selection that is process based. Returning to this list of variables, several of these variables are highly correlated or define each other, so it does not make sense to throw them all into one multivariate analysis as if it is a mystery. For example, bed elevation, max depth, and hydraulic radius are all highly correlated and redundant. Meanwhile, A and P define Rh, so those 3 are also highly correlated. Similarly, Fr is defined by y and u, so the same situation arises. This "throw everything into the soup" strategy of multivariate analysis is not wise and possibly not technically sound, but the authors can review the PCA assumptions and limitations to evaluate that- not worth my time to re-study up on PCA. Even if it is technically ok, it still doesn't make any sense as a strategy as if we do not already know how these variables relate to each other- we do know exactly how they relate.

P.9. I am just not understanding why anything in Figure 4 and the associated results text is actually new results or anything other than trivial findings. By definition of variables, A, Rh, and y are positively correlated, while Fr is going to be negatively correlated to y and positively correlated to u. Also, Z has to be negatively correlated to A, Rh, and y. This is all be definition. PCA is not required to know this. Further, I do not agree that the PCA is adding any fundamentally new or useful information for riffle-pool delineation compared to wisely selecting the few independent variables underlying the physics-based analytical relations, especially bed elevation, width, and possibly slope, as together these three control relative velocity between riffle and pool units for a fixed discharge. If the channels are meandering, then thalweg planform curvature would be important, too, as it is well known in the physics to control meander migration. In fact, it is unclear and technically unsound to exclude metrics of channel width from this analysis, as width is the underlying independent variable influencing all the other variables in the list except for detrended bed elevation and depth (which of course are the same thing just inverted and with different vertical datums). The authors need to set up this methodology better to justify why it is necessary and better than what I am proposing as an easier, more process-based approach or else I do not see how this PCA analysis is meritorious.

p.9, lines 3-4. The claim that each descriptor adds additional information about the bedforms is easy to show as not true. Rh is defined by A and P, so how is Rh fundamentally new and additional as opposed to using a combination of A and P, unless one defines the mathematical operation of division as adding new content, which it does not. This continues the theme of my last few comments. The authors are applying blind statistical methods to what is a pure analytical problem with 100% defined and known elements. There is no additional information beyond the independent variables and the math operators to combine them into A, Rh, and Fr.

Response:

In the initial version of the paper, we were comparing the wavelet-based method with two benchmark methods: the BDT (O'Neill and Abrahams, 1984), and an index method that consists in affecting a different numerical value for each class of a given variable/degree of freedom, and then sum these individual index functions into a composite one.

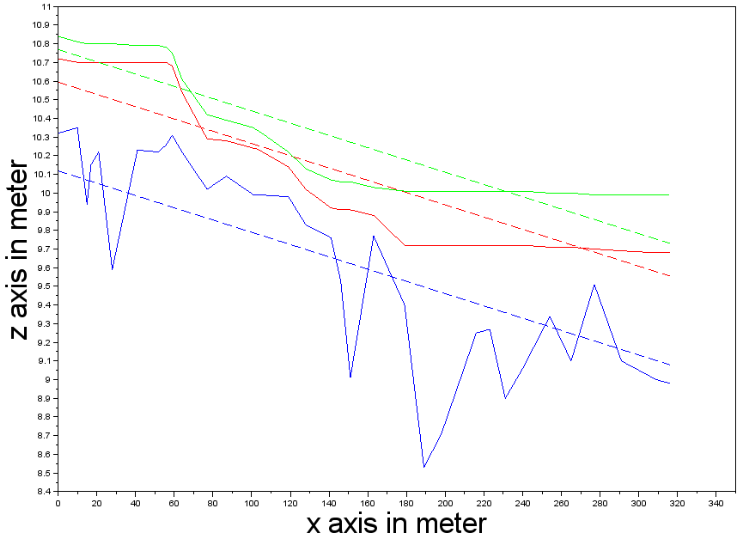
The major concerns are not about the index method in itself, but on the choice of the variables/degrees of freedom. Initially we used the first three axes of a Principal Component Analysis as the degrees of freedom, a choice which has very poor physical meaning. We will entirely cut out this method and focus only on wavelets by using three classical variables: velocity, hydraulic radius (or the closely related cross-sectional averaged depth), and bed shear stress in addition to the planform variable: planform curvature angle.

p. 8, section 4, line 8. The topic of detrending is a huge issue that requires a bit of unpacking in the writing here, because the outcome of riffle-pool delineation can be largely depending on this very choice based on my own sensitivity analysis of this situation using different detrending methods. Earlier in the manuscripts the authors wisely commented about all the different way different authors measure and analyze pool spacing data (e.g., p.6, line 22). Well, the same challenge arises with detrending. There is no universally right or wrong way given the diversity of purposes for detrending, but each option has consequences for the scientific outcome for a specific purpose, especially for identifying the magnitude and length of residual highs and lows in a bed profile. Without going into all the options, what I request is that the authors state what type of detrending they did. If linear, then was it one line per site (presumably no reach breaks within a site, but there could be) and was care taken to insure that the line began and ended at the same relative elevation to avoid biasing the slope, which is a significant problem.

Response:

The procedure that we followed to construct the detrended bed elevation relies on the bed elevation and all water surface levels to avoid biasing the slope. For example, given a reach with N surveyed cross-sections in two discharge stages $Q_1$and Q_2, we define the bed elevation as $z_{talweg}(x)$ and the two water surface levels $z_{ws}(x, Q_1)$ and $z_{ws}(x, Q_2)$. For the detrended bed elevation according to that, it is $Z = z_{talweg} - \mathrm{z}_{trend}$, where $\mathrm{z}_{trend} = \mathrm{S} \times x + b_t$, S and b_t are solutions of the system below.

$$\begin{bmatrix} x_1 & 1 & 0 & 0 \\ x_2 & 1 & 0 & 0 \\ \vdots & \vdots & 0 & 0 \\ x_N & 1 & 0 & 0 \\ x_1 & 0 & 1 & 0 \\ x_2 & 0 & 1 & 0 \\ \vdots & 0 & \vdots & 0 \\ x_N & 0 & 1 & 0 \\ x_1 & 0 & 0 & 1 \\ x_2 & 0 & 0 & 1 \\ \vdots & 0 & 0 & \vdots \\ x_N & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} S \\ b_t \\ b_{Q_1} \\ b_{Q_2} \end{bmatrix} = \begin{bmatrix} z_{\text{talweg}}(x_1) \\ z_{\text{talweg}}(x_2) \\ \vdots \\ z_{\text{talweg}}(x_N) \\ z_{\text{ws}}(x_1, Q_1) \\ z_{\text{ws}}(x_2, Q_1) \\ \vdots \\ z_{\text{ws}}(x_N, Q_1) \\ z_{\text{ws}}(x_1, Q_2) \\ z_{\text{ws}}(x_2, Q_2) \\ \vdots \\ z_{\text{ws}}(x_N, Q_2) \end{bmatrix}$$



As mentioned in the figure, the bed elevation is in blue, water surface for Q_1 is in red and for Q_2in green, the stippled lines are the trends.

p.9, lines 10-12. This single long sentence attempting to explain a sequence of mathematical steps applied to some data is opaque to me as a reader, as is plot (a) in Figure 5. This should be written out more thoroughly and clearly in steps. For example, presumably the smoothed data is each XS spatial series, but then what constitutes the "sampling" that is "homogenized"? I neither understand the samples nor what homogenization is and why it is needed. Is homogenization the same or different from normalization in this study? If so, why call it two different things that creates reader confusion, but if not then what is it? Sometimes normalization means the strict application of the function that makes the data fit the normal probability distribution while more often it just means to divide variable by another.

Response:

This data goes through some processes; first, detrending the variables (as bed elevation), then sampling all variables, this process is a linear interpolation with spacing of 1m or smaller. Second, normalizing and centering them which are just the variable minus its mean divided by the standard deviation. The formulation of smoothing was wrong; this treatment that we performed is a general removal of very low frequency components (wavelength larger than 7 times the mean bankfull width) before applying thresholds. Since we will not use bed elevation anymore, this processing is no longer relevant.

P. 10, first line. Why is this line bold?

Response:

It's what's concluded from the previous paragraph which defined the index. As said before, this part will be dismissed.

P. 10, equation (5). This equation is an all-or-nothing type approach where every location is either classified as riffle or pool for an individual descriptor. This is in contrast to the aforementioned BDT approach that uses a standard deviation tolerance. Also, the method of Pasternack et al. (ESPL 2018a,b) uses a standard deviation tolerance. It would be useful to explain why no tolerance was applied.

Response:

This section will be completely removed so this discussion is not relevant anymore.

P.10, line 10. From what I gather considering the equations and the potential values of I, the concept here is that for something to be defined as a riffle or pool versus an intermediate MU type, all three descriptor variables must agree and yield the same heavyside function value of 0 (pool) or 1 (riffle). Conceptually, the authors are substituting a cross-check among 3 variables as the countermeasure to cope with uncertainty in place of tolerance within each variable as the countermeasure for uncertainty. I think putting the concept of the method in words like this would help readers understand the strategy and purpose of the math and procedure that is described. However, looking beyond that, one can ask if this actually works? In other words, is there a resiliency against uncertainty gained by using multiple variables and the specific ones chosen?

The authors should address why they think this is so, because this is the kernel of new idea they are proposing but have not actually written out. I have to agree that using more than 1 INDEPENDENT variables would help serve as a check against uncertainty, so that is good idea, but (a) the variables chosen are not independent (both Fr and Rh depend on detrended bed elevation, which is a surrogate for the inverse depth and depth goes into both Fr and Rh) and (b) one can choose to use both a tolerance per BDT and multiple variables per this study. That would yield the best outcome. In Pasternack et al. (ESPL, 2018a,b), we do use both strategies, but for our choice of variables we limit our analysis to only detrended bed elevation and width, as these are the process-based controls on flow convergence routing, they are independent, and they underlie the derivative variables like Fr and Rh. However, we do not use slope, which independently controls velocity and Fr, and we make that choose for a specific process-based reason, but we do exclude it. We also do not look at thalweg planform curvature in those articles, though we have internally thus far. One could reasonably choose to include both slope and thalweg planform curvature. One could also choose to include grain size metrics, as I'm sure prof. Jose Rodriguez would be very insistent on given the importance of that variable to determining relative erosion and deposition on riffle sand pools. Unfortunately, it is incredibly difficult to obtain high-resolution spatial series of substrate grain size as of yet. In any case, I see both positive and negative to what is being done.

At a minimum, the authors can explain the general idea in words as I have done, but then also some defense is needed if the authors stand by the decision of variables chosen, because I see the choice as technically unsound given that they are defining each other as explained.

Response:

As I said before, we will cut out the index method.

P.11, line 2. I see that p.6 line 10 defined lambda-star as "dimensionless pool spacing", yet here that variable has dimensions of m? Something is wrong.

Response:

It's a typo! There is no "m".

p.12, lines 1-2. While most people only apply Fourier analysis to stationary series, the method is not in fact limited as thus, because it can be applied using the "evolutive" methodology to capture non stationary dynamics very similar to what one gets from wavelets. One can reasonably argue that wavelets are superior for non stationary data and because one can apply different wave forms, but to say that Fourier analysis cannot do non stationary analysis is wrong. Many applications of evolutive Fourier analysis exist, but for hydrological data see for example, Pasternack, G. B. and Hinnov, L. A. 2003. Hydro meteorological controls on water level in a vegetated Chesapeake Bay tidal freshwater delta. Estuarine, Coastal, and Shelf Science 58:2:373-393.

Section 5.1. I think there is too much redundancy between what was written about wavelets in section 1 (p. 3, lines 20-26) and this section. The introduction can more simply introduce the idea of it and state the scientific questions and hypotheses associated with using it, but then leave the literature review here, so there is only one literature review. My earlier comments about the literature of applying wavelets to geo/hydro data also apply to this section.

Response:

We will change these paragraphs to:

"Classical mathematical methods, such as Fourier analysis, extract the wavelengths in the frequency domain only for stationary signals but also for nonstationary signals using an "evolutive" methodology based on spectral estimators (Thomson., 1982; Pasternack and Hinnov., 2003). Wavelet transforms can do the same for nonstationary signals and find the localized wavelength but with different waveforms. Analyzing a signal basically consists of looking for similarity between the signal and well-known mathematical functions. In this paper, we use the continuous wavelet transform with the Morlet wavelet (Gabor, 1946) (Fig. 3) applied to spatial series instead of time series, so periods and frequencies in time series are replaced by wavelengths and wavenumbers in spatial series.

The wavelet transform is done by convolving the mother wavelet (the waveform) with the signal data, which begin first with the product of the wavelet and a portion of the signal. That product is then integrated to define a mathematical measure of similarity of that portion of the signal to the reference wavelet. This process is repeated as the mother wavelet is moved along the signal and also dilated or contracted to different spatial scales. Thus the transform is done in space and scale (or frequency) simultaneously (McKean et al., 2009)."

p. 15, line 15. Why choose the Orgeval reach, when it is not the longest or having the most XSs? I already deleted my table where I computed the XS density, so does this reach have the highest XS density? Otherwise, why? of course, why not analyze and compare all 6 reaches, as this is a scientific journal article and there could be interesting results in comparing the different reaches? The method itself of applying wavelet analysis to a spatial series is not so novel as to justify limiting to only 1 reach as a single case study.

Table 4. I do not understand. Previously it was stated twice that only 1 reach was assessed but now here are data comparing all six reaches. I think the writing of the manuscript should be improved to explain what is going on better. If all six reaches were in fact tested with wavelet analysis, then some comparison between reaches would be interesting for section 5.

Response:

As I said in the paper this is just a reach example. In the revised paper we will present all the 6 reaches.

Figure 8. This figure shows a fundamental problem with the wavelet methodology as the preferred tool for mapping riffle and pools as well as quantifying their spacings. Specifically, it cannot return results for some distance at the start and end of the spatial series. In the case shown, there is only results for the range of ~ 81-241m out of 318 m. That leaves a whopping 50% of the reach unassessed. Wow. That's a lot of lost information. Of course, the longer the series and the more frequent the XS sampling, the less loss, but there will always be a loss. This makes the method less valuable than alternatives that retain the information.

Section 6.2 This section now states that the comparison is limited to only 81<x<241 m. That's problematic because it's not a fair test of the actual utility of the wavelet method leaving half the reach unevaluated. This should be stated clearly. The comparison is still useful but it does have this huge caveat. A method that leaves half the reach unevaluated can never be better than one that assess the whole reach, if the goal is to characterize the whole reach.

Section 6.1. Authors must clarify if the score technique is applied to the entire reach length or only the length for which results overlap. I think one must count the whole reach as it is a deficiency of the wavelet method that it leaves 50% of reach 6 unevaluated. Whatever the authors are doing, they should clarify that.

Response:

The origin of this problem is the Cone of Influence; it is the region of the wavelet spectrum in which edge effects become important.

Of course we can say the same think for reach length and number of morphological units as for the number of cross-sections: the larger it is, the more robust the results will be, and the smaller the relative portion of “unassessed length” will be. Edge effects due in the cone of influence are clearly a limitation of the wavelet analysis, since it is an analysis in space and scale (x,k) simultaneously. The method has the drawbacks of its advantages, it still remains a powerful tool for non-stationary analysis. Some authors choose to pad the data series with zeros in order to get results on the whole available length. We chose not to use such a padding, which may introduce bias. We prefer a shorter series of local wavenumber K(x), than a longer, potentially biased one.

p. 17, results header. Some authors like to blend methods and results in paired couplets working through a manuscript, and that is most appropriate when one couplet build son the results of another, but then one would not call section 6 here a results section, as many results have already been presented. If I was the associated editor for this manuscript, I would require the authors to separate the methods content from the results content and go with the traditional ordering of the scientific method, because there is no reason not to. One can state the methods from sections 4 and 5 in one unified methods section and then state the results in a unified results section. As the two sections do not build on each other, then one does not need to use the couplet approach. Then, one can have methods and results subsections for the inter comparison analyses. Finally, discussion should stand alone after all results are presented.

Section structure. I think there are problems with the way the manuscript’s sections are structured. In general I can follow what the paper is trying to do, but the structure would be better following a traditional scientific method with all methods first then all results second, ands then all actual discussion last. By mixing them all up it is somewhat confusing and more importantly, impossible to tell what methods have answered what important scientific questions. For example, from the structure it is difficult to tell if this study is only a methodological comparison or also a scientific contribution presenting new results about pool spacings that can be compared with the results of other studies. It would be a shame to do all this work and have no contribution to the question of pool spacing in different river types. But getting back to my main concern here, the discussion, if present at all, iOS hidden in bits throughout the manuscript and would work better if isolated and thoroughly presented.

Response:

That’s true, for that we will reorganize as presented before.

Discussion section 6.3. These paragraph primarily consistent of more results not previously present, but there is a bit of discussion, too. Specifically, all the text in this section from page 19 line 18 to page 21 line 20 are purely results. In fact, p. 21 line 10 even says, “these results: : :” so the authors view these as results too. Really, there is no suitable discussion putting the results of this study into the larger context of methods and results about riffle-pool ID-ing and quantifying their spacings. There should be such a discussion.

Response:

These results will be transferred to the discussion section. The part where we said "these results" is just an error of wording. In the discussing part we will discuss also results of cross-section spacings and their influence on the results according to the Pasternack et al. (2018b) and Legleiter (2014b).

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Automatic~~Wavelet and index methods for the~~ identification of alternating morphological units in river channel using wavelet analysis and ridge extraction~~pool-riffle sequences~~

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Abstract The accuracy of hydraulic models depends on the quality of the bathymetric data they are based on, whatever the scale at which they are applied. ~~(e.g., 2D or 3D reach-scale modeling for local flood studies or 1D modeling for network-scale flood routing).~~ The along-stream (longitudinal) and cross-sectional geometry of *natural* rivers is known to vary at the scale of the hydrographic network (e.g., generally decreasing slope, increasing width)~~, etc.),~~ allowing parameterizations of main cross-sectional parameters with large-scale proxy such as drainage area or bankfull~~a reference~~ discharge~~ quantile~~ (an approach coined downstream hydraulic geometry, DHG). However, higher-frequency morphological variability (*i.e.*, at river reach scale) is known to occur for many stream types, associated with varying flow conditions along a given reach, as for instance the~~:~~ alternate bars or the~~,~~ pool-riffle sequences and~~,~~ meanders~~, etc~~. To consider~~better take~~ this high-frequency variability of the geometry in the~~bedforms into account in~~ hydraulic models, a first step is to design robust methods to characterize the scales at which it occurs. In this paper, we introduce new wavelet analysis tools in the field of geomorphic analysis (namely, Wavelet Ridge Extraction), in order to identify the pseudo-periodicity of alternating morphological units from a general point of view (focusing on pool-riffle sequences) for six small French rivers. This analysis can be performed on a single variable (univariate case) but also on a set of multiple variables (multivariate case). In this study we chose a set of four variables describing the flow degrees of freedom: velocity, hydraulic radius, bed shear stress, and a planform descriptor which quantifies the local deviation of the channel from its mean direction. Finally, this method is compared with the Bedform Differencing Technique (BDT), by computing the mean, median, and standard deviation of their longitudinal spacings. The two methods show agreement in the estimation of the wavelength in all reaches except one. The aim of the method is to extract a pseudo-periodicity of the alternating bedforms that allow objectively identifying morphological units in a continuous approach with the respect of correlations between variables (*i.e.*, At Many Station Hydraulic Geometry, AMHG) without the need to define a prior thresholds for each variable to characterize the transition from one unit to another. ~~propose and benchmark several methods to identify bedform sequences in pool-riffle morphology, for six small French rivers: the first one called the index method, based on three morphological and hydraulic descriptors; the second one called wavelet ridge extraction, performed on the continuous wavelet transform (CWT) of bed elevation. Finally, these new methods are compared with the bedform differencing technique (BDT, O'Neill and Abrahams (1984)), compared by computing a score that gives a percentage of agreement along the total surveyed length and by calculating the number of bedforms and the pool spacings for each method. The three methods were found to give similar results on average for wavelength estimation, with agreement from 64% to 84% and a similar number of bedforms identified. The filter-like behavior of the wavelet ridge analysis tends to give more robust results for the estimation of mean bedform amplitude,~~

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~~which varies from 0.30 to 0.81 with an SNR (signal-to-noise ratio) from 2.68 to 7.91. Otherwise, BDT gives higher mean bedform amplitude but lower SNR values from 0.85 to 1.73.~~

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1 – Introduction:

Hydraulic modeling is~~Flood forecasting models are~~ based on the description of river morphology (cross-sectional geometry), and this is their essential input despite its scarcity and cost of acquisition.~~price (Saleh et al., 2013; Grimaldi et al., 2018).~~ In fact, the most important aspect to know is the river bathymetric data at the local scale, detailed and specific to the site and local conditions (Alfieri et al., 2016). This component is important~~),~~ for an~~the~~ accurate modeling of river hydraulics such as~~, which is essential for predicting floodplain flooding~~ flood ~~forecasting~~ modeling (e.g., Neal et al., 2015; Trigg et al., 2009), river restoration (e.g., Wheaton et al., 2004a), ecohydraulics (e.g., Pasternack and Brown, 2013), environmental modeling and fluvial process (e.g., Rodriguez et al., 2013).~~)~~

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Many researchers are working on determining the best simplified representation of channel geometry (Saleh et al., 2013; Grimaldi et al., 2018~~; Neal et al., 2015; Orlandini and Rosso, 1998~~), based on the variability of cross sections but without the knowledge of the bed elevation variability or the river sinuosity at smaller scale. Other studies focused on the generating of river channels with taking into account the sub-reach scale variability using geostatistics and variogram tools (Legleiter, 2014a, 2014b) or a geometric framework modeling with geomorphic covariance structures (Brown et al., 2014). Longitudinal variability in river geometry may have~~on a small scale. This longitudinal variability in the river geometry has~~ greater impact on the simulation of the water level than the cross-sectional shapes (Saleh et al., 2013) and it must be taken into account in the hydraulic models. ~~designed to improve flood forecasting.~~ This topographic~~longitudinal~~ variability is related to the channel morphology types.

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~~Several classifications of river channel morphology were suggested (e.g., Montgomery and Buffington (1997); Rosgen (1994)). These classifications are broken down into five major categories, based on variables such as channel patterns and channel slope (Robert, 2014). In this paper, we retain the following five main alluvial reach morphologies: cascade, step-pool, plane bed, pool-riffle, and dune-ripple (Montgomery and Buffington, 1997).We summarize all these types in Fig. 1 where each morphology is defined with its characteristics.~~

In this study, we focus mainly on alternating alluvial channels especially pool-riffle sequences, even though the method~~methods~~ presented here could be used to analyze any alternate morphological units (MUs).~~identify sequences of various bedforms.~~ The objective is to provide a continuous description of geometric and flow patterns along a reach, a description that could be subsequently used to create a synthetic river as in the RiverBuilder (Brown et al., 2014). To do that we calculate the ~~identify the pool (or riffle) spacing or~~ dimensionless reach~~reach's~~ wavelength λ^*~~, in the river channel,~~ which is the distance between pools (or riffles) divided by average channel width (e.g., Richards, 1976a; Keller and Melhorn, 1978; Carling and Orr, 2000) or bankfull width (e.g., Leopold et al., 1964).~~ In this paper, we use a normalization by the bankfull width (w_{bf}).~~

~~$\lambda^* = \frac{\lambda}{w_{bf}}$~~ ~~(1)~~

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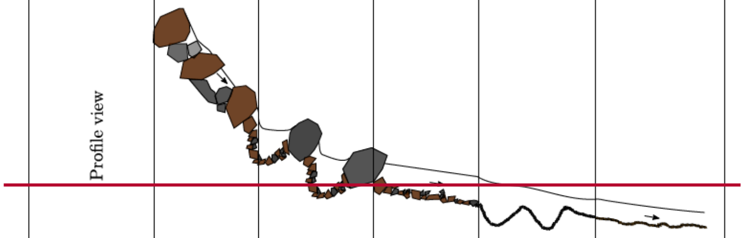
~~with λ the reach wavelength in meters and w_{bf} the reach average bankfull width in meters. The purpose of this identification is to produce a high-frequency variability of cross sections in order to apply it to hydraulic models (see section 2).~~

	Cascade	Step-pool	Plane bed	Pool-riffle	Dune-ripple
Profile view					
Pool spacing $\lambda^*_{w_{bf}}$	< 1	1 to 4	None	5 to 7	5 to 7
Slope	> 0.065	0.03 to 0.065	0.015 to 0.03	< 0.015	< 0.015
Typical bed material	Boulder	Cobble-Boulder	Gravel-Cobble	Gravel	Sand

~~Figure 1.~~1 – 1 – State of art methods for a quantitative assessment of morphological variability within a reach:

Morphological units are topographic forms that shape the river corridor (Wadeson, 1994; Wyrick et al., 2014). They form alternating and rhythmic undulations continuously varying along the river (Thompson, 2001). This continuity is difficult to represent, for this reason most of the methods that model these patterns divide the topography into discrete units to analyze them. However, this may seem artificial and arbitrary (Kondolf, 1995; Wyrick et al., 2014).

Among the most frequently observed alternating MUs, pools ~~Five essential river morphologies with their typical bed materials, the reach profile corresponding to each type, bed slope, typical pool spacing w_{bf} with, $\lambda^*_{w_{bf}}$ the reach wavelength in meters and wbf the average of the bankfull width in meters. These characteristics are taken from the Montgomery and Buffington (1997) study.~~

~~Pools~~ and riffles have been recognized as fundamental geomorphological elements of meandering streams (Krueger and Frothingham, 2007). ~~For many years, many researchers have been trying to develop techniques to identify pools and riffles. These studies may include bed material size (e.g., Leopold et al. (1964); Mosley (1982)), water surface slope (e.g., Yang (1971)), ranges of water depths and velocities (e.g., Allen (1951); Hirsch and Abrahams (1981); Clifford (1993)), bed topography (e.g., Richards (1976a); O'Neill and Abrahams (1984)), Froude number (e.g., Wolman (1955); Jowett (1993); Danehy and Hassett (1996); Kemp et al. (2000)), and descriptions of the water surface characteristics (e.g., Mosley (1982)).~~

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~~From a morphological point of view, pool-riffle sequences are defined as rhythmic undulations in bed topography (O'Neill and Abrahams, 1984). According to Richards (1976a), that definition is better than those based on hydrodynamic variables (e.g., Froude number, velocity) because it changes less with discharge.~~ In fact, pools are located in the outer edge of each meander loop and defined as topographic lows along a longitudinal stream profile with high depth and low velocity (Fig. 1 (A),~~2~~ (B) and (D)) and research has shown that they generally have an asymmetrical cross section shape. Conversely, riffles are topographic highs with shallow depths and moderate to high velocities located in the straight parts of the reach between adjacent loops (Fig. 1 (A),~~2~~ (C) and (D)) and~~that~~ have symmetrical cross section shapes (O'Neill and Abrahams, 1984; Knighton, 1981).

For many years, many researchers have been trying to develop techniques to identify MUs~~All these identification methods, which we present in detail in the following section, have shown limits in calculating the wavelengths of pool-riffle sequences~~ and ~~in most cases their results are often difficult to interpret in terms of bedform amplitude. This amplitude, which varies according to each bedform, goes with the notion of the pseudo period. We therefore choose to work with wavelet analysis, a new method in the hydraulic and morphological field, that estimates the local variability strength of a signal and allows one to extract the signal amplitude and wavelength. The wavelet transform has been used for numerous studies in several domains,~~ especially ~~geophysics and electronics (Torrence and Compo, 1998), and to analyze time series that contain nonstationary power at many different frequencies (Daubechies, 1990). In this study we apply continuous wavelet transform (CWT) to spatial series instead of time series, to calculate the dimensionless pool (or riffle) spacing~~ ~~λ^* between r_{i-1} and r_i intervals and between p_{i-1} and p_i intervals.~~

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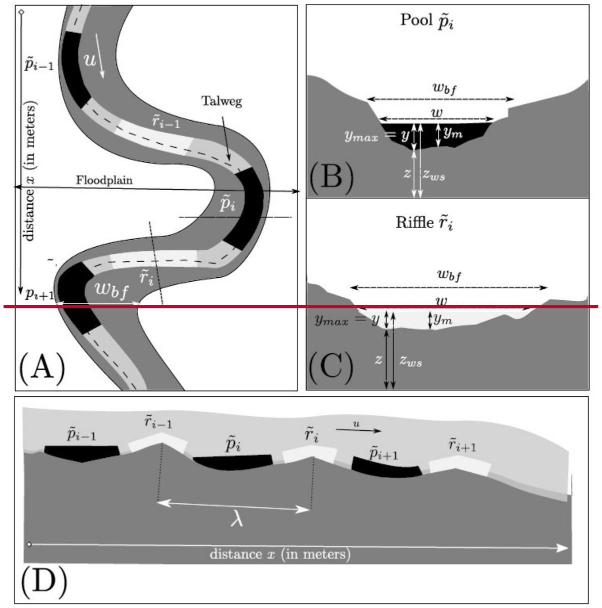

~~**Figure 2.** Different views of pool-riffle sequences. (A) Plan view pattern that includes bankfull width w_{bf} , floodplain extent, talweg line, velocity u, pool interval abscissa (p_{i-1}, p_i, and p_{i+1}), and riffle interval abscissa (r_{i-1} and r_i); (B) cross-sectional view of a pool in the interval p_i with a section width w and a steeper water depth y calculated from the talweg elevation, which is the deepest part of the bottom, and $y = y_{max} = z_{ws} - z$ with z is the bed elevation and z_{ws} the water surface elevation, and y_m the mean water depth; (C) cross-sectional view of a riffle in the interval r_i with a shallower water depth y, higher bed elevation z and high bankfull width w_{bf}; (D) longitudinal profile that makes it possible to see the water surface, the bed slope, the~~ pools and riffles using hydraulic variables or topographic ones, or both (table 1). In the one dimensional identification, some studies used bed topography only to determine the characteristics of MUs.~~, and the wavelength λ calculated between two successive riffles or pools~~

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~~In fact, the choice of the BDT is explained in the paper of Krueger and Frothingham (2007), which finds that the BDT is a more appropriate technique to use to identify these bedforms than the Fr method, especially during low flow.~~

~~2 – Pool-riffle and pool spacing identification:~~

~~Among the morphological methods to identify pool-riffle sequences, the regression analysis by~~ Richards (1976a) proposed the zero-crossing method which fits a regression line to the longitudinal profile of the bed elevation and defines pools as points that have negative residuals and riffles as points with positive residuals. ~~The limitation of this method is that small-scale undulations in the bed topography are incorrectly identified as separate bedforms and can be classified as pools or riffles. This is why~~ O'Neill and Abrahams (1984) developed the Bedform Differencing Technique (BDT)~~BDT~~ as a refinement of Richards' methodology. This one~~Other researchers have investigated the accuracy and agreement of pool-riffle identification methods (e.g., Frothingham and Brown (2002) compared two geomorphological methods of pool-riffle identification: BDT by O'Neill and Abrahams (1984) and the areal difference asymmetry index by Knighton (1981)).~~

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~~The BDT~~ uses bed elevations measured at a fixed interval along the channel to~~. Using this data, we~~ calculate the bed elevation difference series between local extrema (maximum and minimum) of the bed profile. The BDT introduces a tolerance value (T), which is the minimum absolute value of the cumulative elevation change required for the identification of a pool or riffle. The value of T is based on the standard deviation (S_D) of the bed elevation difference series and eliminates the erroneous classification of small undulations in the bed profile. Another method proposed by Knighton (1981) as the Areal Difference Asymmetry Index which is defined as the ratio of the difference between the area of the right and the left of channel centerline on the total cross-sectional area to identify the location of pools and riffles by their symmetrical or asymmetrical areas. On the other hand, some studies focused only on hydraulic parameters to identify MUs. For example, Yang (1971) proposed an identification of pools and riffles using the energy gradient and~~Several values of T should be tested, and for odd-numbered series that follow each bedform, the value of the cumulative is updated and the absolute value of the cumulative is compared with T to ascertain whether the series culminates in a pool or riffle (O'Neill and Abrahams, 1984).~~

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~~However, what a hydrologist would classify as a pool or riffle would not necessarily agree with the classification of a geomorphologist (Krueger and Frothingham, 2007). In fact, hydrologists define pools and riffles by flow parameters such as water depths, velocities (Allen, 1951), water surface slope (Yang, 1971) and Froude number (Jowett, 1993). Yang (1971)~~ affirmed that the fundamental difference between riffles and pools is the difference in energy gradients. Also, Jowett (1993) proposed a classification criterion with

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Froude number and velocity/depth ratio to distinguish between pools, runs, and riffles. ~~, and in a complete cycle of a pool-riffle sequence, the riffle is defined as the portion that has an energy gradient (water surface slope) steeper than the average energy gradient of the complete cycle, whereas the pool is the portion that has an energy gradient milder than the cycle average.~~

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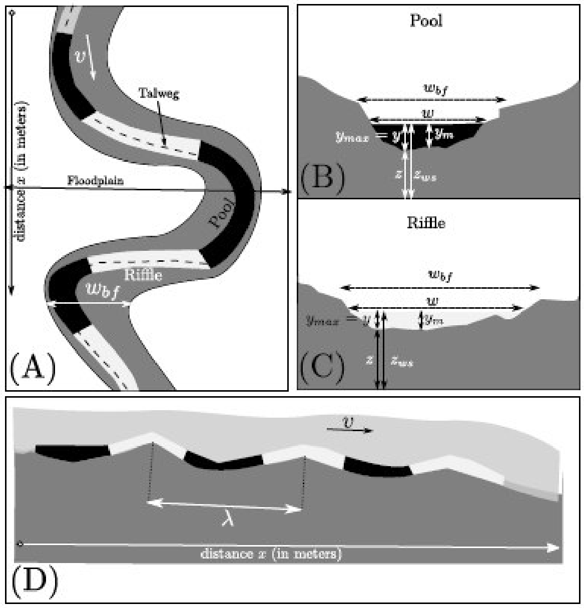

Figure 1. Different views of pool-riffle sequences. (A) Plan view pattern that includes bankfull width w_{bf}, floodplain extent, talweg line, velocity v, pools and riffles, and channel direction (planform); (B) cross-sectional view of a pool with a section width w and a steeper water depth y calculated from the talweg elevation, which is the deepest part of the bottom, and $y = y_{max} = z_{ws} - z$ with z is the bed elevation and z_{ws} the water surface elevation, and y_m the mean water depth; (C) cross-sectional view of a riffle with a shallower water depth y, higher bed elevation z and high bankfull width w_{bf} ; (D) longitudinal profile that makes it possible to see the water surface, the bed slope, the pools and riffles, and the wavelength λ calculated between two successive riffles or pools

All these methods handle topographic or hydraulic parameters separately. Recently, however, several researchers have improved MUs identification through the use of the covariance of several parameters in a multidimensional approach. Schweizer et al. (2007) used a joint depth and velocity distribution to predict pools, runs, and riffles without the knowledge of the river bathymetry. Hauer et al. (2009) used a functional linkage between depth-averaged velocity, water depth and bottom shear stress to describe and quantify six different hydro-morphological units (riffle, fast run, run, pool, backwater and shallow water) using a conceptual Mesohabitat Evaluation Model (MEM) under various flow conditions. These methods use digital elevation models (DEMs) to extract more information about MUs. In this purpose, Milne and Sear (1997)

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began with depth to define pool-riffle sequences using ArcGis tools and DEMs to model the geometry of river channels based on field surveyed cross-sections on a three-dimensional basis. But, by choosing depth alone, the difference between two bedforms with the same depth becomes difficult to know. In contrary, it is easy with different bed slopes and bed roughness that yield different velocities and shear stresses (Wyrick et al., 2014). So to overcome this and take into account the lateral variation of rivers, Wyrick et al. (2014) proposed a new method for the objective identification and mapping of landforms at the morphological unit scale. They used spatial grids of depth and velocity at low flow estimated using 2D hydrodynamic model and an expert classification scheme that determine the number and the nomenclature of MUs and range of base flow depth and velocity of each type.

Brown and Pasternack (2017) chose two variables: the minimum bed elevation and the channel top width across several flow discharges. They calculated the geomorphic covariance structure (GCS) which is a bivariate spatial relationship amongst or between standardized and possibly detrended variables along a river corridor. They found that there is a positive correlation between these two variables. Also, they used an autocorrelation function and power spectral density to prove a quasi-periodic pattern of wide and shallow or narrow and deep cross sections along the river. This pioneer work and other studies (e.g., Richards, 1976; Carling and Orr, 2002) proved that a single longitudinal cycle may contain a pool with a narrow and deep cross section, a riffle with a wide and shallow cross section, in addition to transitional forms. The work that we present in this paper aim to present a spectral method that extract this pseudo-periodicity from a river in order to characterize the alternating MUs and especially pool-riffle sequences, and to identify the key parameter (the wavelength) that characterizes the scale of variability of the river topography. This information can be further used to build a synthetic river such as the RiverBuilder (Pasternack and Arroyo, 2018) or the channel builder for simulating river morphology of Legleiter (2014).

Some of the methods presented in the literature have shown limits in calculating the wavelengths of pool-riffle sequences, others have given results that are often difficult to interpret in terms of bedform amplitude. This amplitude, which varies according to each bedform, involves the use of the pseudo-period. In fact, few methods are developed to extract this pseudo-period from alternating MUs rivers. We therefore choose to work with wavelet analysis that estimates the local variability strength of a signal and extract the signal amplitude and wavelength. In this study we apply continuous wavelet transform (CWT) to calculate the wavelength λ and the dimensionless wavelength spacing λ^* (longitudinal spacing) which is a normalization of λ by the reach average bankfull width (w_{bf}).

$$\lambda^* = \frac{\lambda}{w_{bf}} \tag{1}$$

Methods	Variables	MUs	References
Control-point method	Energy gradient	Pools and riffles	Yang (1971)
Zero-crossing method	Bed topography	Pools and riffles	Richards (1976a) ; Milne (1982)
Areal difference asymmetry index	Cross-section area	Pools and riffles	Knighton (1981)
Power spectral analysis	Bed topography	Pools and riffles	Nordin (1971) ; Box and Jenkins (1976)
Bedform Differencing Technique (BDT)	Bed topography	Pools and riffles	O'Neill and Abrahams (1984)
Hydraulic characteristics classification	Froude number	Pools, runs, and riffles	Jowett (1993)
3D identification	Water depth	Pools and riffles	Milne and Sear (1997)
Schweizer's method	Water depth and velocities	Pools, runs, and riffles	Schweizer et al., 2007a
MEM Model	Water depth, velocity, and bottom shear stress	Pool, riffle, run, fast run, shallow water, and backwater	Hauer et al (2009), Hauer et al (2011)
Wyrick's method	Water depth and velocity	Pools, riffles, runs, and glides	Wyrick et al. (2014), Wyrick and Pasternack (2014)
Brown and Pasternack method	Minimum bed elevation and channel top width	Pools and riffles	Brown and Pasternack (2017)

Table 1: Review of some methods of morphological units' identification (variable used and MUs types).

In reality, longitudinal spacing λ^* has ~~Jowett (1993) proposed and compared multiple hydrological identification methods (velocity/depth ratio, Froude number, and water surface slope). In fact, the Froude number is the dimensionless velocity/depth ratio $Fr = \frac{u_m}{\sqrt{gy}}$, where u_m is the mean water column velocity, y the water depth, and g the acceleration due to gravity (9.81m.s^{-2}). It relates inertia forces to gravity forces and is important wherever gravity dominates. In addition, the Froude number has been recognized as a criterion to distinguish between pools and riffles (Wolman, 1955; Bhowmik and Demissie, 1982).~~

~~The study of Jowett (1993) suggested that pool and riffle habitats are relatively easy to distinguish, but that run habitats (transitional facies) are difficult to distinguish from riffle habitats. Pools occur only where the local stream gradient is low and riffles or rapids in areas where the gradient is high. Moreover, Allen's classification gave pools a Froude number less than 0.15 and a velocity/depth ratio less than about 0.8, and riffles a Froude number greater than 0.25 or a velocity/depth ratio greater than about 1.8.~~

~~Another study by Krueger and Frothingham (2007) applied a common geomorphological and hydrological method to identify pool-riffle sequences. It compared the identification agreement between the two methods on several reaches on Ransom Creek, New York. Other studies concerning pool-riffle sequences occurred in these decades, for instance de Almeida and Rodríguez (2011) analyzed pool-riffle morphodynamics using unsteady 1-D flow morphology and the bed sorting model operated on a continuous basis. Parker et al. (2008) studied the dynamics and pool-riffle evolution. Moreover, Rodríguez et al. (2013) established detailed laboratory flow measurements that allow for the reconstruction of 3-D flow patterns in a pool-riffle design that aims to provide a level of flow variability similar to what would be expected in a natural stream.~~

~~Furthermore, pool spacings have~~ several definitions. Some authors have defined the wavelength λ as the distance between riffle crests (e.g., Harvey (1975); Hogan et al. (1986)), or~~others have chosen~~ the distance from the bottom of successive pools (e.g., Keller and Melhorn (1973, 1978)). Other authors~~Some~~ have ~~also~~

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chosen channel width w (e.g., Richards (1976a, b); Dury (1983)) instead of~~)), otherwise others have used~~ bankfull channel width w_{bf} (e.g., Leopold et al. (1964)). These differences raise questions about the efficiency~~certainty~~ of these ratios ~~(dimensionless pool spacings λ*)~~ and their dependence on geometric or hydraulic parameters. Moreover, the majority of researchers use the average channel width instead of the bankfull width because both give a similar pool-riffle spacing interval. Here, we are working with w_{bf}~~wbf~~ and with a new~~two~~ wavelength calculation method~~methods (Wavelet & index)~~ that we present in section 3~~identify the part where the pool-riffle sequences are located and their repetitions on the reach~~.

Some researchers have~~A great deal of research has~~ investigated the variability of longitudinal~~pool~~ spacing in relation to geometric or hydraulic parameters. Rosgen (2001) developed an empirical relationship between the ratio of pool-to-pool spacing/bankfull width and the channel slope expressed as a percentage based on a negative power function of slope S:

$$\lambda^* = 8.2513 \times S^{-0.9799} \quad (2)$$

~~$\lambda^* = 8.2513S^{-0.9799}$.~~ In addition, Montgomery et al. (1995) showed that there is an influence of large woody debris (LWD) on channel morphology that leads to a relation between LWD and longitudinal~~pool~~ spacing in a pool-riffle sequence, and found that 82% of pools were formed by LWD or other obstructions, and increased numbers of obstructions led to a decrease in pool–riffle spacing. Moreover, research has linked variation in spacing to channel characteristics including gradient (Gregory et al., 1994). Also, Harvey (1975) showed that pool–riffle spacing correlated strongly with discharges between the mean-annual flood and a 5 year recurrence interval (Thompson, 2001). Recently, Wyrick and Pasternack (2014) measured spacing of six different morphological units using a tool in ArcGIS.

Therefore, the definition of the characteristics and the measurement methods allowed us to expect some variation from one study to another in the estimated relationship between longitudinal~~pool~~ spacing and bankfull width (Richards, 1976a; O'Neill and Abrahams, 1984; Gregory et al., 1994; Knighton, 1998). Aside from the interval [$5w_{bf}$, $7w_{bf}$]~~5wbf ,7wbf]~~ defined by Leopold et al. (1964) and the interval [$2w_{bf}$, $4w_{bf}$]~~2wbf ,4wbf]~~ defined by Montgomery et al. (1995) in forested streams, other values of the spacing longitudinal~~pool~~ exist, such as the Carling and Orr (2000) interval, which is [$3w_{bf}$, $7.5w_{bf}$]~~3wbf ,7.5wbf]~~ and decreases to [$3w_{bf}$, $6w_{bf}$]~~3wbf ,6wbf]~~ as sinuosity increases (Clifford, 1993; Carling and Orr, 2000).

1 – 2 – Study objectives:

The studies that used wavelet analysis in ~~We start with~~ the geomorphological field consist in extracting components~~state~~ of a given spatial series (e.g., w(x), v(x)), but they are not specifically designed to identify pseudo-periodic components in a univariate, let alone in a multivariate case. For this reason, we introduce an automatic procedure called Wavelet Ridge Extraction defined by Lilly and Olhede (2009) and used in this study to extract the longitudinal spacing~~art~~ of the alternating MUs.

The objective is to extract some quantitative properties of these alternating morphological units such as the mean and the median of their longitudinal spacing, with a "continuous" vision of the topography instead of a discrete classification. This will be done by focusing on two numerical criteria computed at reach scale: The distribution of spacings between morphological units (mean, median, etc.) and the evaluation of correlations between all geometrical and flow variables. This work will be done on classical variables such

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as velocity, hydraulic radius and bottom shear stress with the addition of a variable less used in the ~~pool-riffle~~ identification of pools and riffles namely, the local channel direction angle. This variable will be used to evaluate the impact of the river sinuosity in the determination of wavelengths and also in the localization of MUs.

In this study, we first present the dataset of six river reaches in France used for this analysis (~~and pool (or riffle) spacings in~~ section 2). In ~~. We present our reaches and data set in~~ section 3~~. Also~~, we present the Wavelet Ridge Extraction method ~~two methods~~ to identify pool-riffle sequences in the univariate and multivariate cases with four variables (velocity, hydraulic radius, bottom shear stress, and local channel direction angle). Section 4 presents results and compare them with~~several reaches in France. Each method is studied separately in sections 4 and 5. The first one, called the index method, combines hydraulic and morphological descriptors and splits pools and riffles using a threshold on a criterion index. The second one, called wavelet method, uses ridge curve analysis to determine the wavelength and amplitude of the signal that contains the pool-riffle sequences. Section 6 compares these methods and~~ the bedform differencing technique (BDT) developed by O'Neill and Abrahams (1984) to determine if they yield the same results in terms of spacing.~~,~~ To accomplish this, ~~a score is defined to compare the pool-pool and riffle-riffle conformity in the index and wavelet methods. In addition,~~ we calculate the wavelength λ and~~,~~ the longitudinal~~pool~~ spacing λ^{*}.~~*, the number of bedforms for each method, and the results of the hydraulic variables (Fr, Rh, and u/y) for each method, and compare their variations with bankfull width wbf , slope S, and reach length l.~~

2~~3~~ - Data set and study reaches:

Six reaches of small French rivers are used in this study (Navratil, 2005; Navratil et al., 2006): the Graulade at~~in~~ St Sylvain Montaigut (1), the Semme at~~in~~ Droux (2), the Olivet at~~in~~ Beaumont Village (3), the Ozanne at~~in~~ Tirzay lès Bonneval (4), the Avennelles at~~in~~ Boissy-le-Châtel Les Avennelles (5), and the Orgeval at~~in~~ Boissy-le-Châtel Le Theil (6) (Fig. 2~~3~~). These reaches contain mainly ~~were chosen in such a way that we have~~ pool-riffle sequences, they~~i.e., all reaches~~ have slopes between~~less than~~ 0.002 and 0.013 m.m^{-1} (estimated from the talweg elevation which is the lowest point in the section),~~015,~~ mobile gravel beds, stable banks, and well-defined floodplains along at least one side of the channel (Navratil et al., 2006). These reaches are located in the Loire River Basin (four reaches) and the Seine River Basin (two reaches), and their length ranges from 155 to 495~~1034~~ m~~, and their drainage area is from 19 to 268 km^2~~ (Table 2~~1~~). All reaches are located at or near the stream gauging stations of the French national hydrometric network. Long-term (about 20 years) hydrological records are available for most reaches. The ~~(Navratil et al., 2006). In addition, the~~ bankfull widths vary~~width varies~~ from 4 to 12 m, with an average value of about 9 m~~, and the reach's slope is estimated from the talweg elevation (lowest point in the section) and generally these reaches have mild bed slopes~~.

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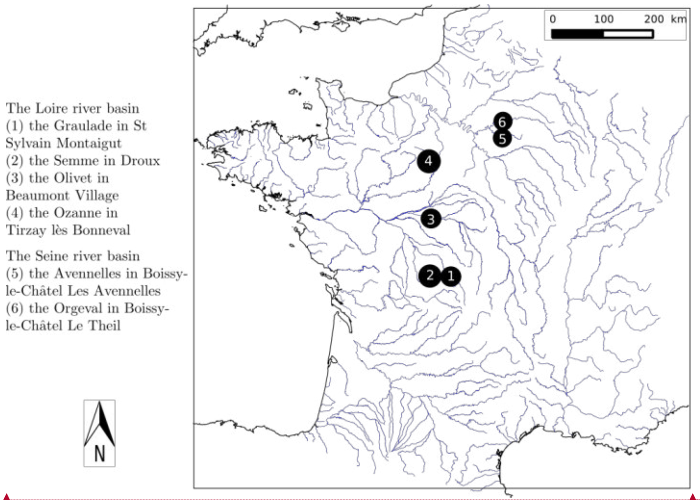

Figure 2~~3~~. Location of the study reaches in France.

Cross-sections were surveyed along the river reaches at the level of hydraulic controls and morphological breaks in order to describe the major variations in terms of width, height, and slope in the main channel and the floodplain and at the level of pool-riffle sequences. Cross-sections and water surface profile measurements were surveyed in 2002 – 2004 covering the main channel and floodplain and using an electronic, digital, total-station theodolite. Water surface profiles were measured at different flow discharges (Navratil et al., 2006).

Reach	**1: Graulade**	**2: Semme**	**3: Olivet**	**4: Ozanne**	**5: Avennelles**	**6: Orgeval**
Reach length L (m)	160	177	495~~1034~~	319	155	318
Number of cross sections	14	32	66~~116~~	26	25	36
~~Drainage area (km^2)~~	~~19~~	~~177~~	~~76~~	~~268~~	~~45~~	~~104~~
Reach gradient S (m.~~/~~m^{-1})	0.0125	0.0044	0.0018	0.0024	0.0060	0.0047
Bankfull width w_{bf} (m)	4	12	6	12	9	10
Average width w_m (m)	2.8	9.3	4.7	7.0	3.3	6.1
Standard deviation $\sigma(w)$ (m)	0.4	1.9	0.9	1.1	0.9	1.0
Surveyed flow discharges (m^3.s^{-1})~~Mean Froude number Fr_m~~	0.22 and 1.26~~33~~	1.85 and 2.41~~0.11~~	0.18, 1.13, 1.72, and 1.99~~0.02~~	0.19, 0.33, 0.8, and 11.5~~0.16~~	0.15~~19~~	0.21~~14~~
~~Mean hydraulic radius Rh_m (m)~~	~~0.17~~	~~0.31~~	~~0.46~~	~~0.20~~	~~0.17~~	~~0.28~~
Min discharge Q_{min} (m^3.s^{-1})	0.22~~2~~	1.85~~0.5~~	0.18~~05~~	0.19~~2~~	0.15~~1~~	0.21~~2~~
~~Max discharge Q_{max} (m^3.s^{-1})~~	~~4~~	~~25~~	~~10.5~~	~~20~~	~~14~~	~~30~~

Table 2~~1~~. Characteristics of the six river reaches and their catchment~~basins~~. The bankfull width w_{bf} is taken from the study of Navratil et al. (2006), and the average width w_m, the standard deviation $\sigma(w)$~~), the mean Froude number Fr_m,~~

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~~and the mean hydraulic radius Rh_m~~ are calculated for the minimum discharge used in this study Q_{min}. ~~and for the reach length ℓ used in the comparison section~~

Using this dataset, we solely rely on measurements at the lowest surveyed discharge in the development of the method because it is the discharge through which we can visualize the variability of the bathymetry (alternating morphological units). We select four spatial series:

1) velocity v(x);
2) hydraulic radius $R_h\,(x) = \frac{A(x)}{P(x)} \cong \frac{A(x)}{w(x)}$ with A(x) is the cross-section area and P(x) is the wetted perimeter;
3) Bed shear stress $\tau_b(x) = (\rho g) n^2 v(x)^2 R_h(x)^{-1/3}$ with ρ : water density (1000 kg/m^3) and n is the Manning's roughness coefficient;
4) Local channel direction angle (planform) $\theta(x)$.

All descriptors are derived from in-situ observations taken from Navratil et al. (2006), except the calibrated estimates of Manning's roughness coefficient *n*. These values were estimated by Navratil et al. (2006) using a one-dimensional open channel steady and step backwater model FLUVIA (Baume and Poirson, 1984). However, we will use these in order to compute the bed shear stress $\tau_b(x)$, along the reach: even if partly relies on calibration, it seems a more robust way of computing τ_b than through the finite differentiation of the total head function $\frac{v(x)^2}{2g} + z(x)$ between adjacent cross-sections to get the energy slope J.

The fourth variable chosen is related to the channel planform: we define $\theta(x)$ as the local angular deviation of the channel direction from a lower-frequency curve. There are many possible definitions of this low-frequency behavior, such as parametric splines or Bezier curves; in order to avoid over-parameterization, we define this low-frequency planform as a constant curvature curve, i.e., the best-fitting arc-circle (Fig. 3), a choice suitable for all six reaches studied. Since θ is signed, it is expected to have a pseudo-periodicity which is approximately twice slower as other 1D variables: indeed, a large positive value of θ indicates a counterclockwise deviation from the low-frequency direction, while a large negative value of same amplitude indicates a clockwise deviation. From a hydraulic perspective, both deviations have the same effect since they are symmetrical with respect to the low-frequency direction. For this reason, which chose to analyze the variable $\cos(\theta(x))$.

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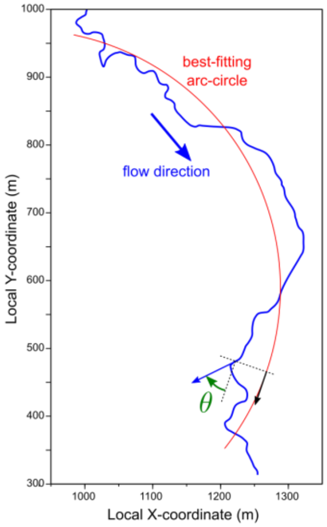


Figure 3. Definition of θ, the local angular deviation of the channel direction from a lower-frequency behavior. Here this low-frequency planform is defined as an arc-circle (illustration on the Olivet River reach). It is worth noting that θ is signed: at the location pointed on the figure, θ is negative.

3 – Wavelet method

~~Many cross sections are surveyed along the river reaches at the level of hydraulic controls and morphological breaks in order to describe the major variations in terms of width, height, and slope in the main channel and the floodplain and at the level of pool-riffle sequences. The hydraulic data set is also surveyed at least for two low discharges and for one almost bankfull discharge (z_{ws}, u, …).~~

~~These data are modeled between Q_{min} and Q_{max} (Table 1) with Fluvia (Baume and Poirson, 1984), a one-dimensional open channel steady and step backwater model. It is based on interpolations rather than extrapolations, it uses simplified shallow water equations, and it assumes that the friction forces are well represented by the Manning-Strickler formulation. The Strickler coefficient is the model's calibration parameter, adjusted visually or with a minimization function to model water depths that correspond to the depths observed.. This code provides us a series of multi-section flows as output for the following variables: bed elevation z, water surface elevation z_{ws}, discharge Q, width w, wetted surface A, wetted perimeter P, hydraulic radius Rh, maximum depth y_{max}, mean depth y_m, velocity u, Strickler coefficient Ks and Froude number Fr, where:~~

~~$Rh = \frac{A}{P}, Fr = u \times \sqrt{\frac{w}{9.81 \times A}} = \frac{Q}{A} \times \sqrt{\frac{w}{9.81 \times A}}, and\ y = y_{max} = z_{ws} - z$ (2)~~

~~4 – Index method~~

~~Bedforms are defined by both morphological and hydrological characteristics. In this paper, we develop a method that combines hydraulic and geomorphological variables into a single index. It takes into account~~

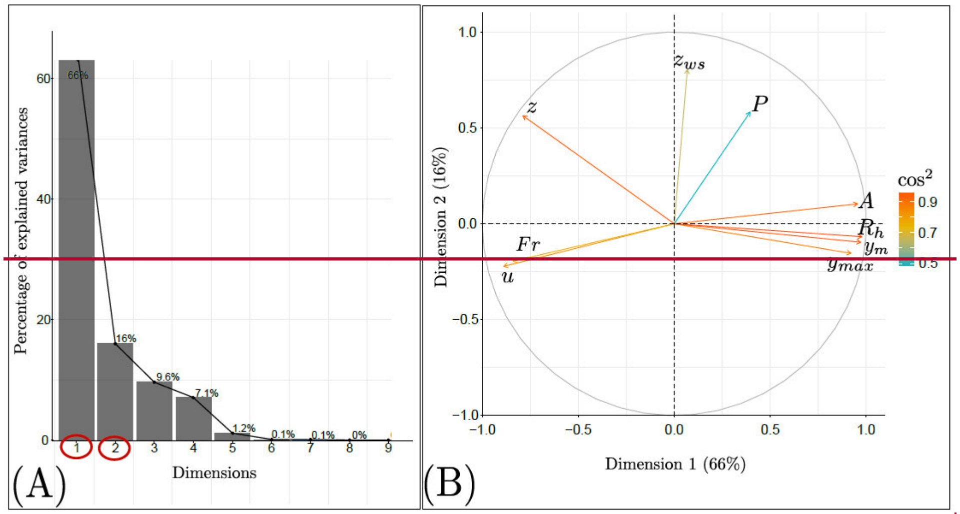
~~several descriptors that are selected using the PCA technique (principal component analysis) during the minimum discharge Q_{min} (Table 1). First, we choose nine variables namely: bed elevation z, water surface elevation z_{ws}, wetted surface A, wetted perimeter P, hydraulic radius Rh, maximum depth y_{max}, mean depth y_m, velocity u, and Froude number Fr. PCA is a method that represents these dependent and intercorrelated variables in order to extract the important information and reproduce it in new orthogonal variables (principal components), and its goal is to find similarities and eliminate redundant variables (Abdi and Williams, 2010).~~

~~Before processing, it is necessary to normalize the data and remove the trend from z and z_{ws}; the detrended variables are then normalized by:~~

~~$p = \frac{p_t - p_m}{\sigma(p_t)}$ (3)~~

~~with p the normalized variable, p_t the detrended variable, p_m its mean, and $\sigma(p_t)$ its standard deviation.~~

~~The PCA assumes that the directions that contain the high variance are the most important (called principal). In Fig. 4 (A), we find two dimensions that contain the most explained variances, the first and the second ones, so we will work on these two axes. Figure 4 (B) illustrates the results and shows the representation quality (cos^2) of the variables on the PCA graphs, which is the square of the coordinate of the variable and it is also represented by the arrow's length. A high cos^2 indicates a good representation of the variable on the main axes, and in this case, the variable is positioned near the correlation circumference circle. A low cos^2 indicates that the variable is not perfectly represented by the main axes, and the variable is close to the circle's center. Consequently, to eliminate the redundancy and accurately characterize the bedform variability, according to Fig. 4 and the results of all the reaches, three descriptors are chosen to define the index for all reaches: bed elevation z, hydraulic radius Rh, and Froude number Fr.~~



~~**Figure 4**. Results of the PCA for the Orgeval reach. (A) Bar plot that represents the percentage of explained variances within the dimensions axis; it limits the number of axes to a number that represents high variance. We keep the first~~

~~two main components (Dimension 1 and 2) which contain an acceptable percentage of 82% of information (variances) in data; (B) this graph is known as the circle of correlations represented on the two chosen axes 1 & 2. It shows the relationships between all the variables (bed elevation z, water surface elevation z_{ws}, wetted surface A, wetted perimeter P, hydraulic radius Rh, maximum depth y_{max}, mean depth y_m, velocity u, and Froude number Fr), and therefore those that are positively correlated are grouped together. Negatively correlated variables are positioned on opposite sides of the circle's origin. The distance between the variables and the origin measures how representative the variables are (cos^2). Variables that are far from the origin are well represented by the PCA.~~

~~This method combines hydraulic and morphologic parameters because each descriptor provides additional information about the bedform. A position with high (or low) values for this type of descriptor does not absolutely represent a riffle (or pool). To overcome this, Fig. 4 (B) shows correlations between descriptors: it is clear that the hydraulic radius is strongly anti-correlated with bed elevation and Froude number, and bed elevation is correlated with Froude number. So now we can define pools as topographic lows with a lower Froude number and greater hydraulic radius, while riffles as topographic highs with a higher Froude number and lower hydraulic radius. For this, we choose as descriptors the opposite of the hydraulic radius −Rh, bed elevation z, and Froude number Fr.~~

~~We find the same correlations for all reaches. Therefore, we smooth the data, sample the three descriptors, and use the opposite of the hydraulic radius to homogenize the sampling, characterize the ups and downs, and obtain a strong correlation between all descriptors.~~

~~The sampling, in Fig. 5 (A), was performed on normalized descriptors and by interpolation at a 1-m step along the reaches, because subsequent methods require regular samples. From this figure, it can be seen that the sampling results show that **pools are characterized by low descriptor values and riffles by high values.**~~

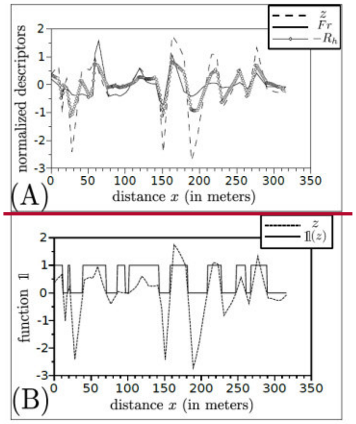
~~The identifying technique of pool-riffle sequences is based on an index that is defined as a function:~~

$$I(x) = \frac{1}{N}\sum_{j=1}^{N} 1(p_j(x)) \tag{4}$$

~~with N the number of the p_j descriptors chosen and 1 the Heaviside step function, defined as:~~

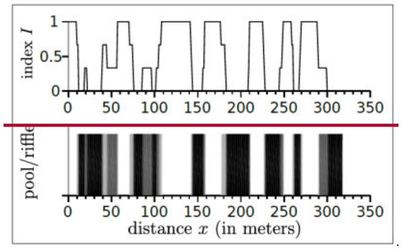
$$1(p_j(x)) = \begin{cases} 1 \; if \; p_j(x) > 0 \\ 0 \; otherwise \end{cases} \tag{5}$$

~~The function 1 returns to 1 if the normalized descriptor is positive, otherwise it returns to 0 (e.g., bed elevation z in Fig. 5 (B)).~~



~~**Figure 5.** (A) The sampled and normalized descriptors for the Orgeval reach. z bed elevation, Fr Froude number, and −Rh opposite of the hydraulic radius, represented on the x axis, which is the distance in meters; (B) the Heaviside step function 1 applied to bed elevation z of the Orgeval reach and represented at the same figure, the objective is to calculate 1 of each descriptor and to take their average.~~

~~This method is applied to the three descriptors (the opposite of hydraulic radius −Rh, bed elevation z, and Froude number Fr) for the six reaches. The index I, in Fig. 6, can take four different values (0, 1/3, 2/3, and 1). In fact, we observe that these results are depicted in stairs, and to make the identification of the bedform easier, we introduced colored bars in Fig. 6 that represent pools with black, riffles with white, and the intermediate morphologies (runs, flat, or rapids) with gray.~~



~~**Figure 6**. Index function I, applied to the Orgeval reach, varies between (0, 1/3, 2/3, and 1). It is depicted on the x axis, which represents the longitudinal distance in meters. The pool-riffle sequences are identified by a spectrum that represents pools in black, riffles in white, and intermediate morphologies (runs, flat, or rapids) in gray.~~

~~By ignoring the intermediate morphologies, we present the discrete pool-riffle identification of the Orgeval reach in Table 2 with 16 bedforms, eight pools, eight riffles, an average wavelength of 38.5 m for riffles and 39.7 m for pools, and $\lambda^* \approx 3.9m$.~~

~~**Interval abscissa (m)**~~	~~**[0,12.5]**~~	~~**[12.5,40.5]**~~	~~**[40.5,45.5]**~~	~~**[45.5,57.5]**~~	~~**[57.5,75.5]**~~	~~**[75.5,105.5]**~~
~~**Index method**~~	~~Riffle~~	~~Pool~~	~~Riffle~~	~~Pool~~	~~Riffle~~	~~Pool~~

~~Interval abscissa (m)~~	~~[105.5,143.5]~~	~~[143.5,158.5]~~	~~[158.5,182.5]~~	~~[182.5,210.5]~~	~~[210.5,227.5]~~
~~Index method~~	~~Riffle~~	~~Pool~~	~~Riffle~~	~~Pool~~	~~Riffle~~
~~Interval abscissa (m)~~	~~[227.5,248.5]~~	~~[248.5,261.5]~~	~~[261.5,269.5]~~	~~[269.5,290.5]~~	~~[290.5,317.5]~~
~~Index method~~	~~Pool~~	~~Riffle~~	~~Pool~~	~~Riffle~~	~~Pool~~

~~**Table 2.** Index method results for the Orgeval reach, showing interval abscissas and the corresponding pool/riffle, we find 16 bedforms, eight riffles, and eight pools~~

~~5 – Wavelet method~~

Classical mathematical methods, such as Fourier analysis, extract the wavelengths in the frequency domain ~~only~~ for stationary signals, but can also be used for nonstationary signals using an “evolutive” methodology based on spectral estimators (Thomson., 1982; Pasternack and Hinnov., 2003).~~,~~ Wavelet transform standardly does~~transforms can do~~ the ~~the~~ same for nonstationary signals: analyzing~~ and find the localized wavelength. Analyzing~~ a signal basically consists in~~of~~ looking for local similarity between the signal and a given waveform (the wavelet).~~well known mathematical functions.~~ In this paper, we use the continuous wavelet transform with the Morlet wavelet (Gabor, 1946) (Fig. 4) applied to spatial series instead of time series, so periods and frequencies in time series are replaced by wavelengths (in m) and wavenumbers (in rad.m^{-1}). The choice of the Morlet wavelet is justified by its interesting analytical properties (see Appendix B).~~and wavenumbers in spatial series. In this section, we introduced the wavelet analysis for spatial series in section 5.1, the wavelet ridge analysis and steps to extract amplitude and wavelength of the pool-riffle channel in section 5.2, and finally the pool-riffle identification for the Orgeval reach in section 5.3.~~

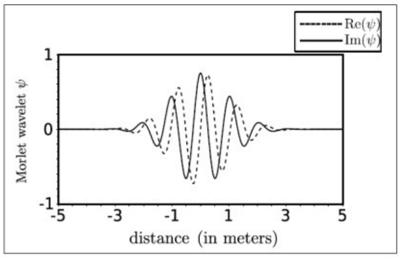


Figure 4. Morlet mother wavelet function. The plot gives the real part and the imaginary part of the wavelets in the space domain (distance).

The wavelet transform uses a whole family of “daughter” wavelets generated by scaling and translating the mother wavelet ψ ; the value of the transform at location x and scale s is the scalar product of the signal and this daughter wavelet $\psi_{s,x}$.

~~5 – 1 – Definitions:~~

~~Wavelets are used because of their aptitude to space-wavenumber and space-scale analysis. The advantage of analyzing a signal with these functions, is that it makes it possible to study the features of the signal locally with the level of detail matched to their scale (Kumar and Foufoula-Georgiou, 1997). They are mathematical functions that cut up data into different frequency components and then study each component~~

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~~with a resolution matched to its scale; however, the structure of the calculations remains the same (Graps, 1995).~~

Wavelet analysis is very popular in many fields such as fluid mechanics (e.g., Schneider and Vasilyev (2010); Higuchi et al. (1994); Katul et al. (1994); Katul and Parlange (1995b, a)), meteorology (e.g., Kumar and Foufoula-Georgiou (1993); Kumar (1996)), ~~and~~ geophysics (e.g., Ng and Chan (2012); Grinsted et al. (2004)), hydrology~~)). But recently, hydrologists have been interested in this tool as well~~ (e.g., Rossi et al. (2011); Schaefli et al. (2007); Nourani et al. (2014)), and geomorphology (Lashermes et al., 2007; Gangodagamage et al., 2007; McKean et al., 2009).~~but working only on time series with continuous or discrete wavelet transformation.~~ In the literature of the alternating bedforms identification, McKean et al. (2009) used Derivative of~~present study, we tested~~ a Gaussian wavelets (DOG) of order 6 to investigate the~~new wavelet analysis ridge curve analysis on~~ spatial patterns (pools and riffles) of channel morphology and salmon spawning using a one-dimensional elevation profile of the channel bed morphology. ~~series with the Morlet mother basis function represented in Fig. 7. Its expression is:~~

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In this study, we use another application of the wavelet analysis called the wavelet ridge extraction method (Mallat, 1999; Lilly and Olhede, 2010). This analysis is based on the existence of special space/wavenumber curves, called wavelet ridge curves or simply ridges (Lilly and Olhede, 2010), where the signal concentrates most of its energy (Carmona et al., 1999; Ozkurt and Savaci, 2005). Along such a curve, the signal can be approximated by a single component modulated both in amplitude and frequency. So, the rationale behind the method is that the existence of alternating morphological units along a reach (such as pools-riffles sequences) could be translated into a pseudo-periodicity in geometric and flow variables. Hence, identifying these bedforms amounts to identifying a local wavenumber K(x) and phase Φ (x) for each variable, a task that can be performed by wavelet analysis and especially Wavelet Ridge Extraction (Mallat, 1999; Lilly and Olhede, 2010).

3 – 1 – Wavelet analysis and ridge extraction:

Few methods in the literature have been trying to identify river characteristics with wavelets. For example, Gangodagamage et al. (2007) used Wavelet Transform Modulus Maxima (WTMM, Muzy et al., 1993) in a fractal analysis to extract multiscale statistical properties of a corridor width. Procedures such as the WTMM consist in extracting components of the signal, but they are not specifically designed to identify pseudo-periodic components in a univariate, let alone in a multivariate case.

In the present study, we tested a new wavelet ridge analysis on spatial series with the Morlet mother basis function represented in Fig. 4. Its expression is:

$$\psi(\eta) = \pi^{-\frac{1}{4}} e^{i\beta\eta} e^{-\frac{\eta^2}{2}}$$

(3~~6~~)

With~~Where~~ ψ is the mother wavelet function that depends on the dimensionless "position" parameter η and β is the dimensionless frequency, here taken to be 6 as recommended by Torrence and Compo (1998). Starting with this wavelet mother, a family $\psi_{s,x}$ called wavelet daughters is obtained by translating and scaling ψ.

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$$\psi_{s,x}(\eta) = \frac{1}{\sqrt{s}}\,\psi\left(\frac{\eta - x}{s}\right), x \in \mathbb{R}, s > 0$$ (4~~7~~)

With x~~where x~~ is the translation offset~~factor~~, which represents a position at which the signal is analyzed, and s the dilation or scale factor.

If s > 1, the daughter wavelet has a frequency lower than the mother wavelet, whereas if s < 1, a wavelet with a frequency higher than the mother wavelet is generated.

Given a spatial series $f(\eta)$, its continuous wavelet transform $W[f](x,s)$ with respect to the wavelet ψ is a function of two variables where:

$$W[f]: \mathbb{R} \times \mathbb{R}_+^* \to \mathbb{C}$$

$$(x,s) \to \frac{1}{\sqrt{s}} \int_{-\infty}^{+\infty} f(\eta)\psi^*\left(\frac{\eta - x}{s}\right) d\eta$$ (5~~8~~)

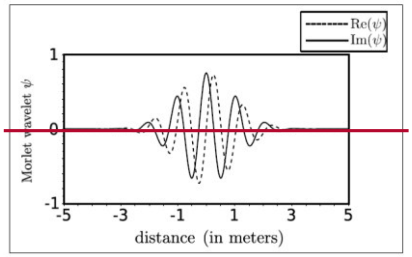
(*) indicates the complex conjugate. This complex function can also be written as:

$$W[f](x,s) = R(x,s)e^{i\phi(x,s)}$$ (6~~9~~)

With~~where~~ R is the absolute value (modulus) and ϕ the phase (argument) at position x with the scale s.

$$R(x,s) = |W[f](x,s)|$$ (7)~~10)~~

$\phi(x,s) = Im(\ln W[f(x)]\,(x,s))$ ~~$\arctan\left(\frac{Im(W[f](x,s))}{Re(W[f](x,s))}\right)$~~ (8~~11~~)



~~**Figure 7.** Wavelet Morlet mother function, the plot gives the real part and the imaginary part of the wavelets in the space domain (distance).~~

To respect the nomenclature in the spatial definition and facilitate the extraction, we choose the angular wavenumber (in rad.m^{-1}) $k = \frac{2\pi}{\lambda}$ instead of the scale factor. We associate a wavelength $\lambda = 2\pi\alpha s$ with the scale parameter s, where α is the Fourier factor associated with the wavelet, and~~with $k_\psi = \frac{1}{\alpha}$ the peak wavenumber of the mother wavelet, and~~

$$\alpha = \frac{2}{\beta + \sqrt{2 + \beta^2}}$$ (9~~12~~)

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$$s = \frac{1}{\alpha k}\cancel{\frac{k_{\psi}}{k}} \qquad (10\cancel{13})$$

Thus, the wavelet transform of the function f(x) is defined in the space-wavenumber as:

$$\begin{gathered} W[f]: \mathbb{R} \times \mathbb{R}_{+}^{*} \rightarrow \mathbb{C} \\ (x,s) \rightarrow \sqrt{\alpha k}\int_{-\infty}^{+\infty} f(\eta)\psi^{*}\big(\alpha k(\eta - x)\big)d\eta \end{gathered} \qquad (11\cancel{14})$$

Except for the channel angle, all input variables are always positive and may substantially vary in magnitude so we perform~~5 – 2 – Wavelet ridge analysis:~~

~~Using~~ the wavelet transform on the Neperian logarithm of these variables. The whole analysis is performed in *Scilab*, using an adaptation of the toolbox by Torrence and Compo (1998) [*atoc.colorado.edu/research/wavelets/*].

The complex ~~ridge analysis, we extract the oscillatory components, characterized by pool-riffle sequences along the river, and their properties from the space-frequency representations of~~ wavelet transform can be classically visualized using a scalogram, i.e., a colored map of the modulus *R*(*x*,*k*) in the (*x*,*k*) plane (Fig. 5 bottom). The wavelet analysis neglects parts of the signal at both extremities of the series: this is the *cone of influence* (Torrence and Compo., 1998), the region of the wavelet spectrum in which edge effects become important. However, as explained previously, the complex transform also yields a phase Phi(x,k) in rad (Eq. (8)) which can also be plotted in the same plane (Fig. 5 top). In our study, we will search for special ~~. This analysis is based on the existence of spatial~~ space/wavenumber curves mainly using the phase information, i.e. search for *phase* ridges as opposed to *amplitude* ~~, called wavelet ridge curves or simply~~ ridges (Lilly and Olhede, 2010).

In section 3.2, we give a rigorous definition of Wavelet Ridge ~~), where the signal concentrates most of its energy (Carmona et al., 1999) and where R2 is high. A ridge curve is a group of~~ points and curves in a univariate case (i.e., a single spatial series). Then, in section 3.3, we generalize the definition to the multivariate i.e. when the series consists in several correlated variables~~called ridge points~~.

3 – 2 – Univariate case:

In the univariate case, we choose a single variable *f* (velocity, hydraulic radius, bed shear stress, or local channel direction angle). ~~The objective is to extract these ridge points that contain not only the wavelength but also the amplitude of the signal. This signal represents the pool-riffle shape. Therefore, the wavelet ridge is used to identify frequency-modulated sinusoidal signal components using a curve at the space-k plane along which the energy is locally maximum (Ozkurt and Savaci, 2005). Indeed, this method is a filtering tool that evacuates all details below the wavelength resolution (or k-resolution) and which keeps only its pattern. In this paragraph, we detail the ridge points extraction for Morlet wavelets.~~

For the wavelet $\psi(\eta)$, the ridge point of $W[f](x,s)$ is a space/wavenumber pair (x, k) satisfying the ~~amplitude and~~ *phase ridge point conditions* (Lilly and Olhede, 2010):

$$\cancel{\frac{\partial}{\partial k}Re(\ln W[f(x)]\,(x,k)) = 0} \qquad \cancel{(15)}$$

$$\frac{\partial}{\partial x}Im(\ln W[f(x)]\,(x,k)) - k = \cancel{\alpha k k_{\psi} =} 0 \qquad (12\cancel{16})$$

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or, according to the definition of the phase (Eq. 8) :

~~These conditions state that for each fixed position point x, a phase ridge point ϕ (or an amplitude ridge point) corresponds to the wavenumber at which a local maximum in the transform magnitude occurs (Lilly and Olhede, 2010).~~

~~According to the mathematical development of the partial derivatives in Appendix B and since we are limited only to extracting the phase ridge points $\phi(x,k)$, we have $Im(\ln W[f(x)](x,k)) = \phi(x,k)$, and the equation to solve becomes:~~

$$\left.\frac{\partial \phi}{\partial x}\right|_{(x,k)} - k = 0$$

(13~~17~~)

This condition states that ~~Therefore, we search locally in position x for~~ the rate of change of transform phase at scale *k* exactly matches *k* at location *x*; from this condition,~~wavelet daughter function whose wavenumber K(x) takes~~ the instantaneous frequency~~maximum variance~~ of the signal can be derived (Lilly~~,~~ and Olhede, 2008 ; Lilly and Olhede, 2010). The sets of points satisfying~~represents~~ the condition form~~pool-riffle sequences.~~

~~To determine the function K(x), we will work in the space of two variables (x,k) using the phase function $\phi(x,k)$ of the wavelet transform, or more precisely its partial derivatives in x (see Appendix B). In fact, the function K(x), that we are looking for could be seen as~~ a parametric curve (ridge curve) noted (*x*, *K*(*x*)) implicitely~~x,K(x)) defined on $\mathbb{R} \times \mathbb{R}_+$ of the wavelet transform. It is therefore implicitly~~ defined by:

$$\left.\frac{\partial \phi}{\partial x}\right|_{(x,K(x))} - K(x) = 0$$

(14~~18~~)

~~The curve K(x) belongs to the level 30 curves that verify Eq. (17).~~ This property is illustrated in Fig. 5, where a ridge curve is superposed both on the scalogram and on~~8 (A):~~ the phase map.~~set of points of K(x) (in thick white) verifying Eq. (18).~~

There may be several curves that verify the Eq. 14~~this property~~; in practice we choose curves~~the curve~~ that cross~~crosses~~ continuously ~~(without interruption)~~ the domain of the wavelet transform (from one cone of influence to another) and belong to the region where a maximum power of the wavelet is. This curve K(x) ~~). It~~ also represents the local wavenumber, which is defined on a support ℓ < L named assessed length, with L the total reach length.

The phase function Φ is then obtained by evaluating the function $\phi(x, k)$ along the curve (x, K(x)), in thick black in Fig. B1 (A) in Appendix B-1.

$$\Phi(\mathrm{x}) = \phi(x, K(x))$$

(15~~19~~)

In the end, we can extract the wavelength function of pool-riffle sequences, which corresponds to a pseudo-period function of the signal f, and which is:

$$\lambda(\mathrm{x}) = \frac{2\pi}{K(x)}$$

(16~~20~~)

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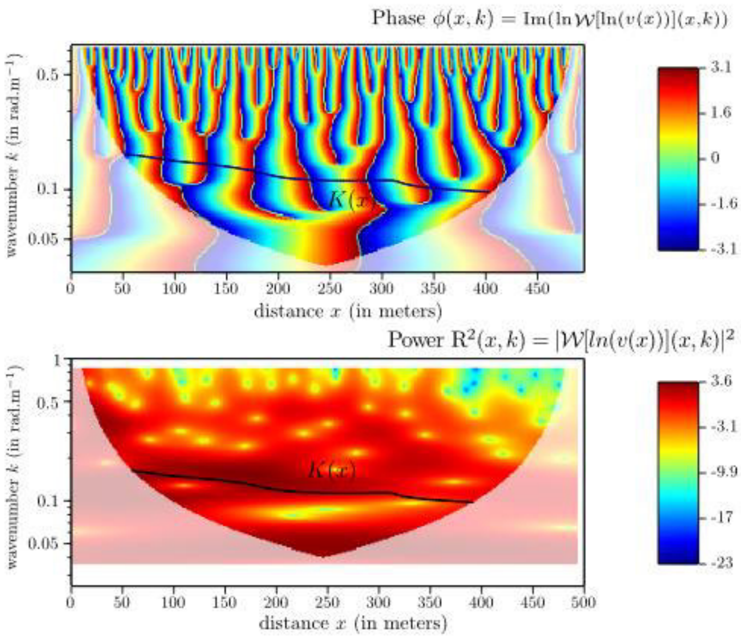

Figure 5: First plot: the phase function from which we get the function K(x); Second plot: the power of the wavelet with the region where there is maximum variability depicted by the black curve K(x) (ridge curve). These two figures are represented in a wavenumber/distance space for the Olivet River and the wavelet transform is performed on the logarithm of the velocity. The part of the figure with low opacity shows the cone of influence which is neglected in this study (edge effects are more important for short wavelengths than for long wavelengths).

Also, the shape's amplitude A_m,~~;~~ with which pools and riffles vary, is corrected by a coefficient $\sqrt{\frac{1}{\alpha K(x)}}$~~.~~ This correction comes from the inversion of the direct transformation equation (Eq. 10) which holds the coefficient $\sqrt{\alpha K(x)}$. $\cancel{\sqrt{\frac{k_\psi}{K(x)}}}$

$$\mathrm{A}_m(\mathrm{x}) = |W[f](x,K(x))| \sqrt{\frac{1}{\alpha K(x)}} \cancel{\sqrt{\frac{k_\psi}{K(x)}}} = R(x,K(x)) \sqrt{\frac{1}{\alpha K(x)}} \cancel{\sqrt{\frac{k_\psi}{K(x)}}} \qquad (17~~21~~)$$

The signal is locally similar to a sinusoid f_{mod} of wavenumber K in rad.m^{-1} which model the variability f. We can define the pseudo-periodic variable as presented in the Fig. 6 with:

~~5 3 Pool-riffle identification:~~

~~In this part, we apply the ridge wavelet analysis, explained in the previous subsection, to the spatial function z (bed elevation) and we limit the study only with univariate analysis of the pool-riffle sequences of the~~

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~~Orgeval reach (6). We use the toolbox of Torrence and Compo (1998) [atoc.colorado.edu/research/wavelets/], and transform it into Scilab and add modifications to extract the wavelength λ and amplitude~~ ~~A_m.~~

~~To obtain the pool-riffle sequences, we define a function~~ ~~I_W, which is extracted from the daughter wavelet:~~

$$f_{mod}(x) = A_m(x)\cos\big(\Phi(x)\big) = A_m(x)\cos(\phi(x, K(x))) \cancel{I_W = A_m\cos(\Phi(x))}$$

(18~~22~~)

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In the example below (Fig. 6), the modeled velocity function follows the variability of the observed velocity, it is a pseudo-periodic, continuous function that approximates the first-order variability of this hydraulic parameter across pool-riffle sequences. The statistics of the K(x) function can be translated into statistics of longitudinal spacings of alternating bedforms, e.g. mean spacing λ^*_{mean} , median spacing λ^*_{median} or spacing standard deviation $\sigma(\lambda^*)$. In Fig. 6 we would find $\lambda^*_{mean} \approx 8.7$, $\lambda^*_{median} \approx 9.12$, and $\sigma(\lambda^*) \approx 0.79$ if we were to analyze velocity only ; The pseudo-periodicity of v_{mod} yields to the identification of 6 pools (white) and 7 riffles (gray).

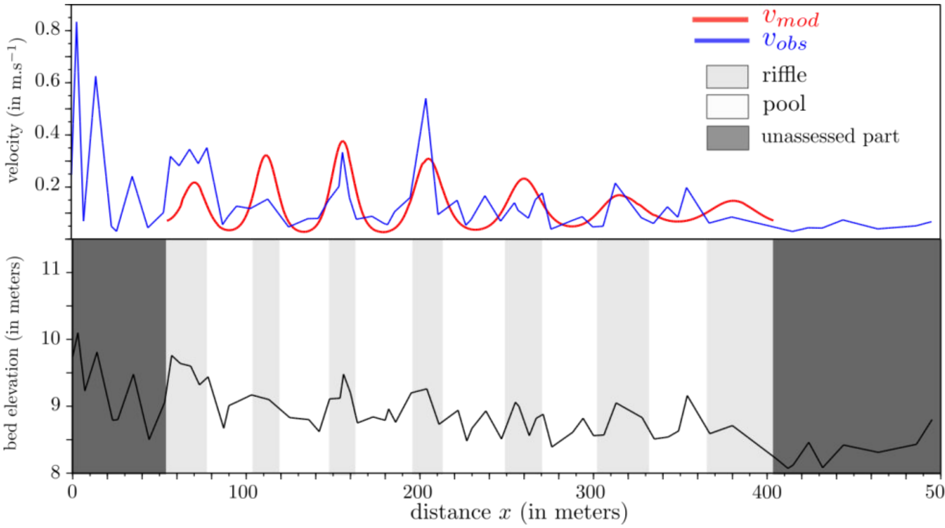


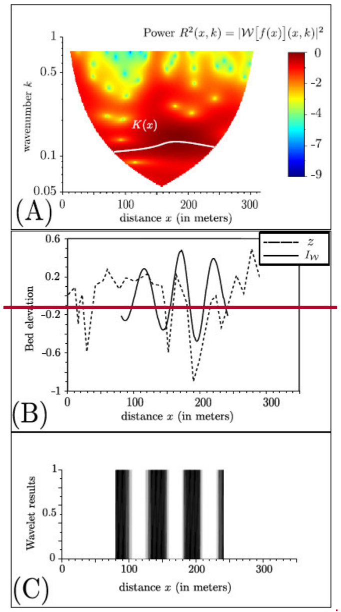
Figure 6: variation of the modeled function f_{mod} which represent the pseudo-periodic variable (e.g., the velocity of the Olivet River) compared to the observed one. This pseudo-periodicity yields to the identification of pools (white) and riffles (gray) in the plot below. The not studied part is due to the cone of influence of the wavelet method.

In the next section, we will extend the definition of phase ridge points and ridges to the case where several variables are sampled along the reach, all of them potentially correlated and embedding information about the pseudo-periodicity of channel hydraulic behavior.

3 – 3 – Multivariate case:

The multivariate case is the extension of the univariate to a set of N real-valued signals, we use the coevolution of more than one variable to extract the wavelength of the reach and therefore identify the pool-riffle sequences. We start by computing the wavelet transform for each variable i = 1..N and extract their phase functions $\phi_i(x,k)$. According to the previous section, univariate ridges curves $K_i(x)$ would be defined by:

~~In fact, we present a wavelet power plot (Fig. 8 (A)) applied to bed elevation z in the wavenumber/distance space to show the higher energy region and the extracting ridge curve that contains all the information about the reach (wavelength, phase, and amplitude). The function $I_{\mathcal{W}}$ translates the ridge curve variability in the spatial domain, it is a frequency- and amplitude- modulated sinusoid, and as a result, it gives the bedform variability represented in Fig. 8 (B). This plot shows great conformity between the bed elevation and the signal identified, and the advantage of this method is that, at different scales, it not only gives the wavelength of the pool-riffle repetitions, but it gives the amplitude of each bedform shape associated with the wavelength. Moreover, wavelet ridge analysis can be extended to the multivariate case (Lilly and Olhede, 2009).~~



~~**Figure 8**. Steps to identify pool-riffle sequences for the Orgeval reach using bed elevation z with the wavelet method. (A) Power of the wavelet, which is represented in a wavenumber/distance space, with the region where there is maximum variability depicted by the white curve (ridge curve); (B) variation of $I_{\mathcal{W}}$ function compared to the bed elevation z. (C) Identification of pools (black), riffles (white), and intermediate morphologies (gray).~~

~~If we analyze the results of this method on the Orgeval reach (6), we find that the wavelet method eliminates part of the bed elevation details and takes the part that contains the high power (Fig. 8 (A) and (B)) on which it identifies the bedforms graphically. Figure 8 (C) shows us the pool-riffle sequences in spectral~~

~~representation as in the index method section. Therefore, we consider that the parts that are in black are pools, white are riffles, and gray represents intermediate morphologies (runs, flat, or rapids).~~

~~By ignoring the intermediate morphologies, we present the discrete pool-riffle identification of the Orgeval reach in Table 3 with seven bedforms, four pools, three riffles, a wavelength of 53.4m, and~~ ~~$\lambda^* \approx 5.3m$~~~~.~~

$$\left.\frac{\partial \phi_i}{\partial x}\right|_{(x,K_i(x))} - K_i(x) = 0$$ ~~**Interval abscissa (m)**~~

(19)~~[~~ ~~**80.5, 101.5]**~~ ~~**[101.5,129.5]**~~ ~~**[129**~~

~~**Wavelet method**~~	~~Pool~~	~~Riffle~~	~~Pool~~	~~Riffle~~
~~**Interval abscissa (m)**~~	~~**[182.5,207.5]**~~	~~**[207.5,234.5]**~~	~~**[234.5,242.5]**~~	
~~**Wavelet method**~~	~~Pool~~	~~Riffle~~	~~Pool~~	

But then the local wavenumber would be specific to a given variable, which is not what we would like. We would rather like to find a common wavenumber for all variables at location *x*, i.e. such that:

~~**Table 3.** Wavelet method results for the Orgeval reach, showing interval abscissas and the corresponding pool/riffle, we find seven bedforms, three riffles, and four pools~~

~~6 – Results and discussion:~~

~~In this section, we present the results, the comparison between methods and the discussion. First, we introduce the comparison method based on a score technique that compares the two methods index and wavelet. Second, we present the application of this comparison on the index and wavelet methods, and we introduce the BDT results. Finally, these results are discussed according to data presented in section 3.~~

~~6 – 1 – Comparison method:~~

~~We compare the wavelet method and the index method using the score technique. The idea is to define a symmetric agreement score that quantifies to what extent the methods conform, it measures at which point we could have the same results, and finally it gives a percentage score that represents the common parts of pools and riffles of the total length.~~

~~Let us assume for example that the wavelet method identifies~~ ~~n~~ ~~pools and~~ ~~m~~ ~~riffles, and the index method identifies~~ ~~n'~~ ~~pools and~~ ~~m'~~ ~~riffles. Consequently, for the wavelet method, the pool intervals of this type of reach are~~ ~~$\widetilde{P_W} = \cup_{i=1}^{n} \tilde{p}_i^W$~~ ~~and the riffle intervals are~~ ~~$\widetilde{R_W} = \cup_{i=1}^{m} \tilde{r}_i^W$~~~~. On the other hand, the pools and riffles identified by the index method are successively~~ ~~$\widetilde{P_I} = \cup_{j=1}^{n'} \tilde{p}_j^I$~~ ~~and~~ ~~$\widetilde{R_I} = \cup_{j=1}^{m'} \tilde{r}_j^I$~~ ~~where~~ ~~$\tilde{p}_i^W$, $\tilde{r}_i^W$, $\tilde{p}_j^I$~~~~, and~~ ~~$\tilde{r}_j^I$~~ ~~are successively pool and riffle interval abscissa number i identified by the wavelet method, and pool and riffle interval abscissa number j identified by the index method. Thus, the score is defined as:~~

$$\left.\frac{\partial \phi_i}{\partial x}\right|_{(x,K(x))} - K(x) \approx 0 \qquad \forall i$$ ~~$score = \frac{\ell(\widetilde{P_I} \cap \widetilde{P_W}) + \ell(\widetilde{R_I} \cap \widetilde{R_W})}{\ell}$~~

(20~~23~~)

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The identification of a “master” ridge point/curve is now a minimization problem. We will define it as a local minimum of the squared norm of the vector $\left(\frac{\partial \phi_1}{\partial x}\Big|_{(x,k)} - k, \frac{\partial \phi_2}{\partial x}\Big|_{(x,k)} - k, \dots, \frac{\partial \phi_N}{\partial x}\Big|_{(x,k)} - k\right)$:

~~With $\ell = \sum_{i=1}^{n} \ell(\tilde{p}_i^W) + \sum_{i=1}^{m} \ell(\tilde{r}_i^W) = \sum_{j=1}^{n\prime} \ell(\tilde{p}_j^I) + \sum_{j=1}^{m\prime} \ell(\tilde{r}_j^I)$ the support of K(x), and $\ell()$ the interval’s length.~~

~~6 2 Application and results:~~

~~Each method scans the bed elevations of the reach and identifies pool-riffle sequences. The number of these bedforms varies from one reach to another and goes from 4 to 49 bedforms. Before presenting the results, we assume that pools and riffles are intervals that are different from what O’Neill and Abrahams (1984) considered in their identification. In fact, BDT assumes it works on points and it is only used to check the wavelength and the number of bedforms of the reach (Table 5).~~

~~Another issue is that the work is done on a length ℓ hundreds of meters long (which is the K(x) support in Fig. 8) in which we represent the results of the three methods at the same time; this length is calculated between the centers of two intervals. In addition, the other intermediate morphologies are ignored in this comparison.~~

~~By studying the case of the Orgeval reach (6), which has an identification interval between 81 and 241 m, and using the results of the two methods illustrated in Fig. 9 below and Tables 2 and 3, a comparison on the common interval is made by this score technique, and yields:~~

$$E(x,k) = \sum_{i=1}^{N} \left(\frac{\partial \phi_i}{\partial x}\Big|_{(x,k)} - k \right)^2 \quad (21$$

~~$\widetilde{P_I} \cap \widetilde{P_W}$ = [80.5,101.5] ∪ [143.5,157.5] ∪ [182.5,207.5] ∪ [234.5,241.5]~~ ~~24)~~ ~~(25~~)

~~$\widetilde{R_I} \cap \widetilde{R_W}$ = [105.5,129.5] ∪ [158.5,182.5] ∪ [210.5,227.5]~~

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This minimum is calculated by searching for the wavenumbers and positions where the derivatives (Equ. 22) of this quantity satisfies these two conditions bellow:

~~So, with a length of $\ell = 161m$~~

$$\frac{\partial E(x,k)}{\partial k} = \sum_{i=1}^{N} \left(\frac{\partial^2 \phi_i}{\partial k \partial x}\Big|_{(x,k)} - 1 \right) \left(\frac{\partial \phi_i}{\partial x}\Big|_{(x,k)} - k \right) = 0$$

$$\frac{\partial^2 E(x,k)}{\partial k^2} = \sum_{i=1}^{N} \left[\frac{\partial^3 \phi_i}{\partial k^2 \partial x}\Big|_{(x,k)} \left(\frac{\partial \phi_i}{\partial x}\Big|_{(x,k)} - k \right) + \left(\frac{\partial^2 \phi_i}{\partial k \partial x}\Big|_{(x,k)} - 1 \right)^2 \right] > 0 \quad (22$$

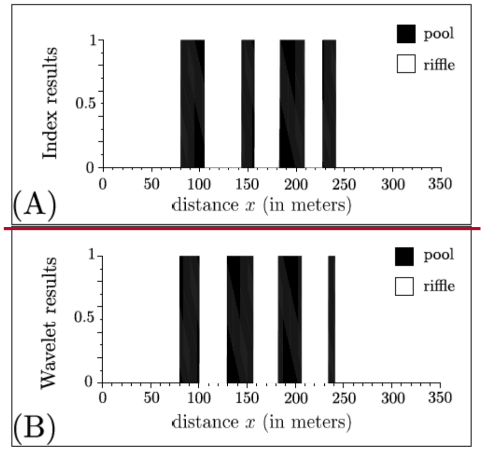
~~score~~ ~~26~~)

~~$= \frac{\ell(\widetilde{P_I} \cap \widetilde{P_W}) + \ell(\widetilde{R_I} \cap \widetilde{R_W})}{\ell} = \frac{67+65}{161} = 82\%$~~

Tableau mis en forme

An illustration of this procedure is given in Fig. 7 for the Olivet River. As mentioned in section 2 the set of variables is $[v, R_h, \tau_b, \theta]$. The power of the wavelet changes according to the variables but the pseudo-period is common to all four variables, which represents a co-evolution of these variables. And by the same procedure as in the univariate case, the phase shift of every variable is calculated by:

~~and then we are able to have a pool-pool and riffle-riffle similarity in 82% of the total length of the reach studied, which means that we have 82% accuracy to find the same bedform using the two methods. If we analyze this reach, we have seven intervals; on each of them we identify the corresponding bedform for each method (Tables 2 and 3) and calculate the score. As a result, we find high percentages for most of the reaches, from 64% to 84%, showing that these two methods are accurate in this paper (Table 4 presents the scores of all the reaches).~~



~~**Figure 9.** Plot showing the identification of pools (black) and riffles (white) ignoring the intermediate morphologies for the Orgeval reach, for the index method (A) and the wavelet method (B).~~

$$\Phi_i(x) = \phi_i(x, K(x)) \qquad (23)$$

~~**Reaches**~~	~~**1 - Graulade**~~	~~**2 - Semme**~~	~~**3 - Olivet**~~	~~**4 - Ozanne**~~	~~**5 - Avennelles**~~	~~**6 - Orgeval**~~
~~**Score**~~	~~84%~~	~~64%~~	~~67%~~	~~76%~~	~~65%~~	~~82%~~

This ridge curve K(x) is common between all variables, yet Φ_i varies according to each variable. Therefore, each one can be represented as a pseudo-periodic function $f_{i,mod}$ with the pair $(K(x), \Phi_i(x))$.

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Tableau mis en forme

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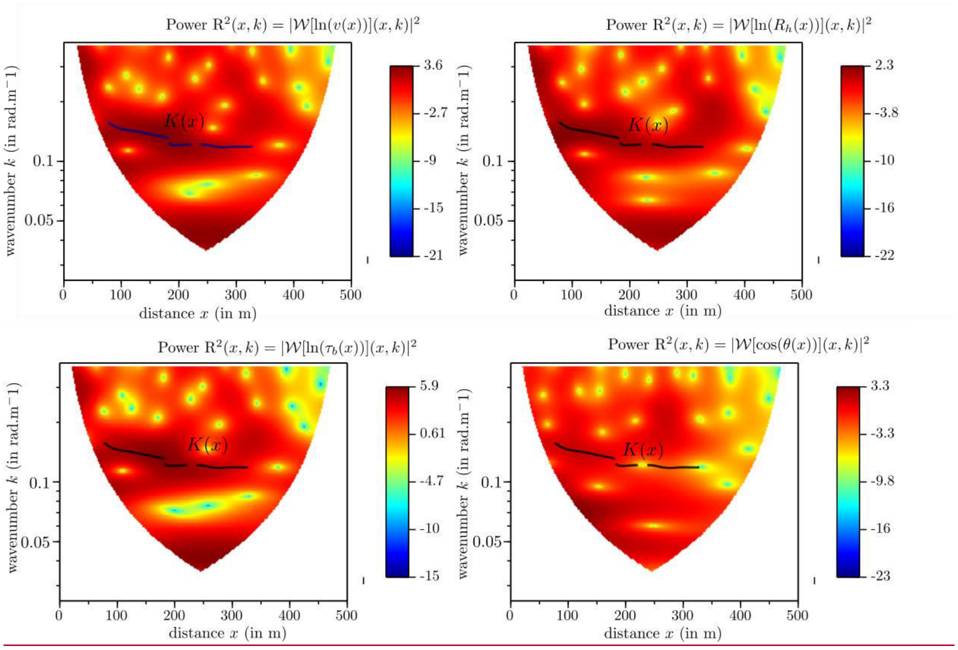

Figure 7: Power of the wavelet of the four variables: velocity, hydraulic radius, bed shear stress, and local channel direction angle. The black curve K(x) is the extracted ridge curve of the Olivet River in the multivariate case.

In our case, after calculating the phase and amplitude, we modelled each variable as in the Eq. 24 and represented them in Fig. 8.

$$f_{i,mod}(x) = A_{i,m}(x)\cos\big(\Phi_i(x)\big) = A_{i,m}(x)\cos(\phi_i(x, K(x))) \qquad (24)$$

The amplitude shape of the modeled variable is calculated by the same way in the univariate case:

$$A_{i,m}(x) = |W[f_i](x, K(x))|\sqrt{\frac{1}{\alpha K(x)}} \qquad (25)$$

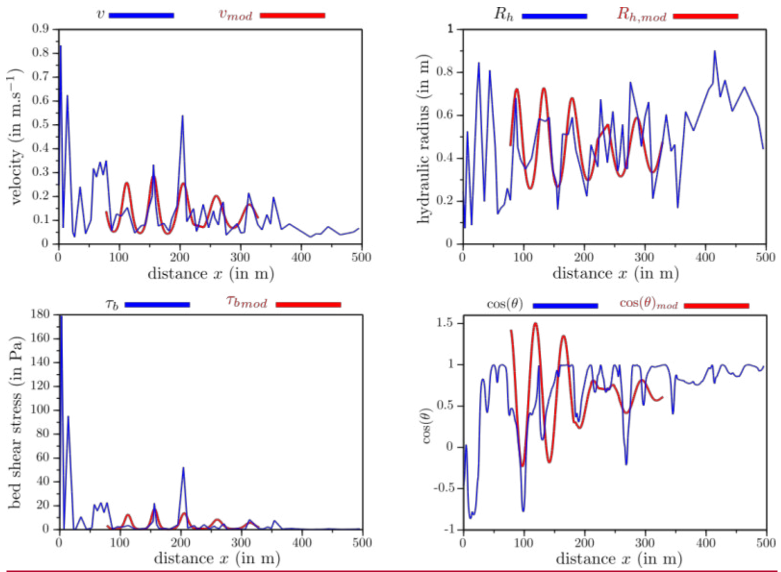

Figure 8: Variation of the modeled function $f_{i,mod}$ which represent the pseudo-periodic variable (in red) for the velocity, the hydraulic radius, the bed shear stress, and the local channel direction angle of the Olivet River compared to the observed ones (in blue).

The results in Fig. 8 show that a common pseudo-period has been successfully indentified and allows a consistent pseudo-periodic representation of all four variables.

Fig. 9 shows the correlations between these variables which are well respected between the three flow variables; an anti-correlated hydraulic radius with bed shear stress and velocity and a strong correlation between bed shear stress and velocity. However, with regard to the angle, the results show a small phase shift which is corrected afterwards. But generally a deviation (clockwise or counterclockwise) from the average direction of the channel (i.e. cos(theta) much smaller than 1) is associated with a low hydraulic radius and large values of taub and U, a consistent characterization of a riffle. This gives us an identification reach features: pools (in white) and riffles (in grey).

As already mentioned in section 3.2 (univariate analysis), the statistics of the K(x) function can be translated into statistics of local wavelength $\lambda(x) = 2Pi/K(x)$, which can in turn be interpreted as statistics of longitudinal spacings of alternating bedforms, e.g. mean spacing λ^*_{mean} , median spacing λ^*_{median} or spacing standard deviation $\sigma(\lambda^*)$. In the example of the Olivet river (Fig. 9) $\lambda^*_{mean} \approx 8.16$, $\lambda^*_{median} \approx 8.62$, and $\sigma(\lambda^*) \approx 0.70$. The pseudo-periodicity of the set $[v_{mod}, R_{h_{mod}}, \tau_{b_{mod}}, \theta_{mod}]$ yields to the identification of 5 pools and 5 riffles.

And then, a continuous topography can be generated that models the observed one using the local wavenumber K(x). The validation of this approach will be undertaken in the next section by comparing these univariate and multivariate approaches by modelling the topography and validating with the measured one to determine how well our approach holds.

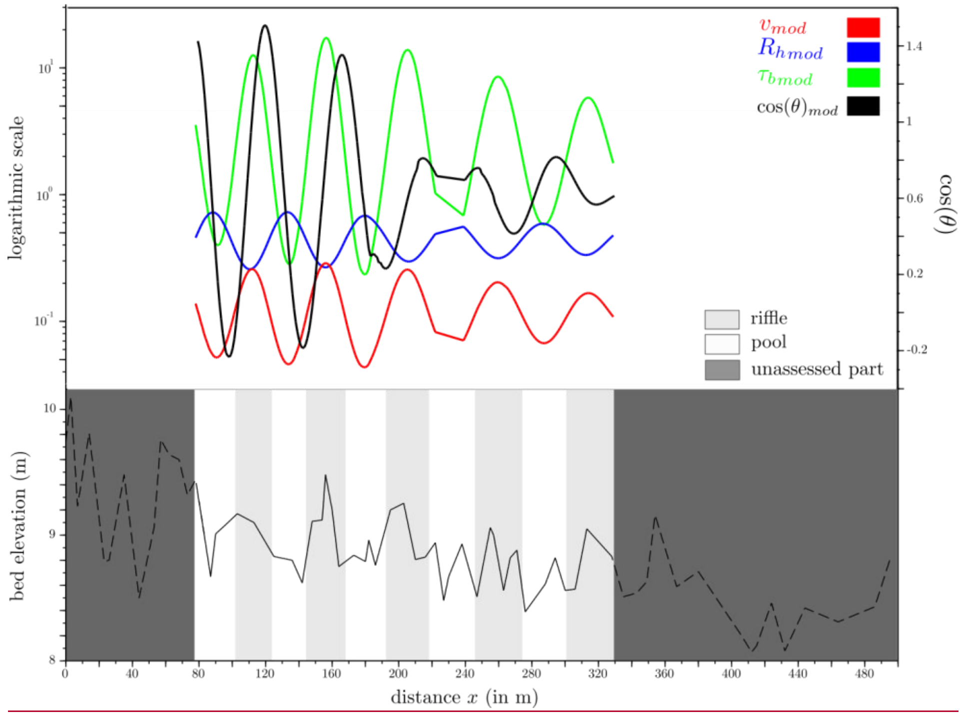

Figure 9: Correlation between the modeled functions $f_{i,mod}$ which represent the pseudo-periodic variables (velocity in red, hydraulic radius in blue, bed shear stress in green, and local channel direction angle in black) of the Olivet river.

4 – Results:

In this section, we present the results of the analysis on the six reaches presented in section 2. We present the comparison between the univariate and the multivariate approaches and a comparison of the multivariate with the benchmark method. The methods are compared in terms of the statistics (mean, median, etc.) they yield. Second, we present the benchmark method called BDT (Bedform differencing technique) and compare its results of the six reaches with the multivariate case.

4 – 1 – Univariate vs Multivariate:

First, both approaches were employed on all reaches to extract statistics such as the mean, median and standard deviation wavelengths of morphological units (pool-riffle sequences). The wavelet method works onto an assessed length ℓ (which is the K(x) support in Fig. 6 and 9) that is generally small compared to the total length of the reach. Consequently, we have results that are valuable only for the lengths shown in Table 3. In this table, we give the values of these lengths for each approach and with the variables used in it. These values generally depend on the number of alternating bed forms and also on the total length of the reach. The greater the number of alternating bed forms and the reach length are, the greater the assessed length is.

Moreover, the multivariate approach takes into account all the variables and therefore looks for a single pseudo-periodicity between the four variables and then we're going to have a pseudo-periodicity that represents the reach and not the chosen variable.

Reaches	Reach length (m)	Assessed length ℓ (m) (Univariate)				Assessed length ℓ (m) (Multivariate)
		Velocity	Hydraulic radius	Bed shear stress	Local channel direction angle	$[v, R_h, \tau_b, cos\theta]$
1: Graulade	160	88	67	72	102	67
2: Semme	177	87	70	89	110	37
3: Olivet	495	349	366	363	365	251
4: Ozanne	319	215	157	151	125	77
5: Avennelles	155	76	70	79	64	60
6: Orgeval	318	142	200	163	140	158

Table 3. Assessed length by the wavelet analysis for all reaches in the univariate case using the velocity, hydraulic radius, bed shear stress, or local channel direction angle and in the multivariate case using all these four variables.

Table 4 gives some statistics on both approaches. Longitudinal spacing is calculated using the wavelengths extracted automatically by the wavelet ridge method from K(x).

We compare the methods in terms of longitudinal spacing (λ^*). In each reach, there seems to be one variable which drives the wavelength identified in the multivariate approach:

- in the Graulade River and, the longitudinal spacing identified using the multivariate approach matches closely the one associated with the hydraulic radius (in the mean and the median with deviation of $0.05w_{bf}$ (Graulade) and $0.28w_{bf}$ (Orgeval)) and also with the local channel direction angle (in the median for the Graulade with a deviation of $0.06w_{bf}$ and in the mean and the median for the Orgeval with $0.06w_{bf}$);
- in the Semme River, it matches those of the local channel direction angle (in the mean and the median with a deviation of $0.14w_{bf}$ and $0.12w_{bf}$ consecutively);
- in the Olivet River, it matches the bed shear stress (in the mean with a deviation of $0.25w_{bf}$) and the velocity (in the median with a deviation of $0.5w_{bf}$);
- in the Ozanne River, it matches those of the hydraulic radius and the velocity (in the mean and the median with a deviation less than $0.6w_{bf}$);
- in the Avennelles, it matches those of the velocity, hydraulic radius, and the bed shear stress (in the mean with a deviation less than $0.15w_{bf}$);
- in the Orgeval River, it matches those of the hydraulic radius (in the mean with a deviation of $0.28w_{bf}$ and the median with $0.06w_{bf}$) and also with the local channel direction angle (in the mean with a deviation of $0.23w_{bf}$ and in the median with $0.11w_{bf}$).

				1: Graulade	2: Semme	3: Olivet	4: Ozanne	5: Avennelles	6: Orgeval
Univariate	Velocity	λ(m)	Mean	23.47	13.86	52.20	37.18	27.32	51.66
			median	24.17	13.93	54.74	36.74	27.17	51.29
			$\sigma(\lambda)$	1.69	0.53	7.75	2.97	1.60	1.70
		λ^*	Mean	5.87	1.15	8.70	**3.10**	**3.03**	5.17
			median	6.04	1.16	**9.12**	**3.06**	**3.02**	5.13
			$\sigma(\lambda^*)$	0.42	0.04	1.29	0.25	0.18	0.17
	Hydraulic radius	λ(m)	Mean	21.74	39.28	47.19	37.73	25.72	45.46
			median	21.41	39.43	46.60	38.47	25.47	48.23
			$\sigma(\lambda)$	0.71	1.19	4.74	2.40	0.66	8.73
		λ^*	Mean	**5.43**	3.27	7.86	**3.14**	**2.86**	**4.55**
			median	**5.35**	3.29	7.76	**3.20**	**2.83**	**4.82**
			$\sigma(\lambda^*)$	0.18	0.10	0.79	0.20	0.07	0.87
	Bed shear stress	λ(m)	Mean	26.07	32.29	47.47	36.43	27.47	51.70
			median	25.92	32.66	45.54	36.30	27.95	51.26
			$\sigma(\lambda)$	1.12	1.68	5.36	1.70	0.73	1.54
		λ^*	Mean	6.52	2.69	**7.91**	3.04	**3.05**	5.17
			median	6.48	2.72	7.59	3.02	**3.11**	5.13
			$\sigma(\lambda^*)$	0.28	0.14	0.89	0.14	0.09	0.15
	$\cos\theta$	λ(m)	Mean	21.14	23.45	40.87	66.31	28.79	50.58
			median	21.32	23.30	39.44	62.98	28.73	49.93
			$\sigma(\lambda)$	0.75	0.95	3.57	7.49	1.47	4.35
		λ^*	Mean	5.28	**1.95**	6.81	5.52	3.20	**5.06**
			median	**5.33**	**1.94**	6.57	5.25	3.19	**4.99**
			$\sigma(\lambda^*)$	0.19	0.08	0.60	0.62	0.16	0.43
Multivariate	$[v, R_h, \tau_b, cos\ \theta]$	λ(m)	Mean	21.54	21.74	48.98	43.89	26.59	48.29
			median	21.55	21.84	51.70	43.49	26.54	48.78
			$\sigma(\lambda)$	0.38	0.85	4.22	0.98	0.40	3.42
		λ^*	Mean	**5.38**	**1.81**	**8.16**	**3.66**	**2.95**	**4.83**
			median	**5.39**	**1.82**	**8.62**	**3.62**	**2.95**	**4.88**
			$\sigma(\lambda^*)$	**0.09**	**0.07**	**0.70**	**0.08**	**0.04**	**0.34**

Table 4. Summary of results for all reaches in the univariate case using the velocity, hydraulic radius, bed shear stress, or local channel direction angle and in the multivariate case using all these four variables. For each variable we compute the mean, median, and the standard deviation σ of the wavelength and the longitudinal spacing. This one λ^* is calculated by $\frac{\lambda}{w_{bf}}$, and w_{bf} is taken from Table 2.

Interestingly, the multivariate estimates of lambda compares with univariate estimates in a similar way:

- The distribution of lambda in the multivariate case is included in the envelope of univariate distributions,
- The dispersion of this multivariate distribution, measured by $\sigma(\lambda^*)$, is always close to the minimum value that can be achieved by any of the univariate distributions.

Hence, the multivariate method improves the identification of the wavelength: it is less sensitive to a local high frequency variation of a given variable if this variation is not associated with a variation of the others variables.

In the following section, we will compare the wavelet method with a benchmark method using talweg elevation.

4 – 2 – Comparison with benchmark method:

In this section, we compare our method's results with a selected benchmark method from the literature. It is called the Bed form Differencing Technique (BDT) introduced by O'Neill and Abrahams (1984). We choose this method instead of threshold methods because the latter require thresholds (expert judgment) collected from the field, which is not possible in our case.

The technique of O'Neill and Abrahams (1984) (BDT)~~**Table 4.** The score technique results~~

~~To validate and discuss these two methods, the technique of O'Neill and Abrahams (1984) (BDT) is chosen. This technique~~ uses a tolerance value (T), which defines the minimum absolute value needed to identify a pool or a riffle (Krueger and Frothingham, 2007). It is calculated using the standard deviation (S_D) of the series of bed elevation differences from upstream to downstream for each reach and corrected by a coefficient chosen according to the reach. For this, we test several tolerance values, and for the Graulade (1), Ozanne (4), Avennelles (5) and Orgeval (6) reaches we find the same results. We choose to check one~~two~~ tolerance value~~values~~ for each reach with $T = S_D$. This method gives pools and riffles positions by assigning a crest as a riffle and a bottom as a pool and therefore the computation of the wavelengths becomes a little difficult. So, we chose to calculate a series of pool-pool and riffle-riffle spacings, their medians, and standard deviations and then calculate their averages~~$T = 2S_D$~~.

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This was applied to all rivers and the results are depicted in the Fig. 10. Statistics of the BDT are shown in Table 5 which displays a comparison between these two types of morphological units' identification and mostly the identification of an average wavelength of the reach.

Fig. 10 shows the BDT results on all reaches, this method relies only on topography to determine the positions of pools and riffles, moreover it also uses a threshold T (tolerance) but the technique does not need a calibration reach or field investigation to know how to set this threshold. In this figure, Round points are pools or riffles and from these points we can calculate the wavelengths and longitudinal spacing of each reach as we stated before.

The work of the wavelet analysis is done on the assessed length ℓ. However, the BDT method works on the total length of the reaches. This was done to determine how effective the wavelength extracted by the wavelet analysis can represent the entire reach even if an entire part is left unassessed.

For the wavelet method (Fig. 9~~8~~), the wavelength extraction is among its objectives, while for the ~~index and~~ BDT, the computation of the wavelength is done a sort of multiple calculations. To compare these two methods, we will use only the longitudinal spacing (λ^*) as a criterion.

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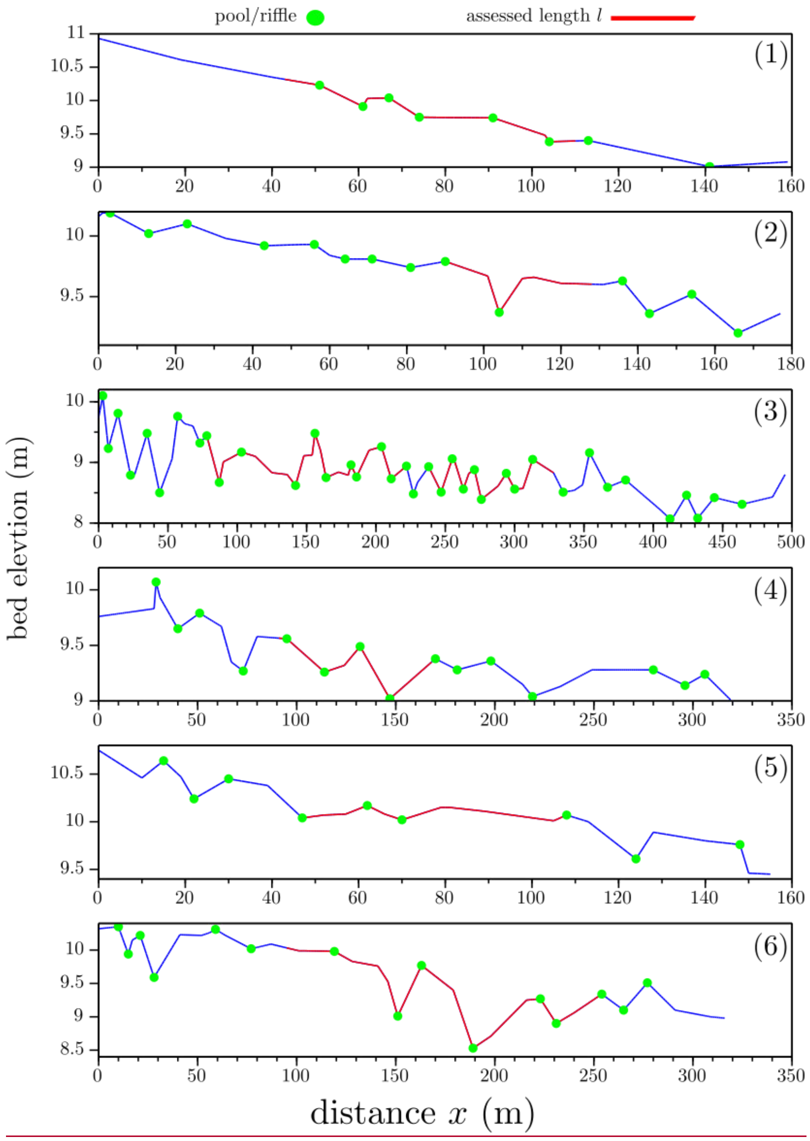

Figure 10: Results of the BDT method using a tolerance equal to the standard deviation on the total length and the assessed one (red) for all reaches (1 to 6). Round points are pools or riffles: pools are high and riffles are low points.

In Table 5, we present results of the BDT on the total length L of all reaches and on the assessed length ℓ. Using the total length L, the longitudinal~~by first averaging the pool-to-pool~~ spacings found with the BDT are close to the ones found with the wavelet analysis (deviation less than 1 time the bankfull width~~, then~~

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~~averaging the riffle-to-riffle spacings, and finally calculating their mean. This kind of calculation is used to prevent overestimation or underestimation of the wavelength. For example, for the Orgeval reach (6), we find a wavelength of 53.4 m~~ for the median), in all the reaches except the Olivet (deviation of $4w_{bf}$). Over the assessed length ℓ we find very similar results with a deviations less than one time the bankfull width. However, the shortening of the length (ℓ < L) reduces ~~wavelet method, 50.8 m for the index and 49.8 for BDT. However, we choose to compare~~ the number of pools and riffles identified (Graulade (1) and Avennelles (5)) and therefore introduces bias. This indicates that a reasonable length is always required to produce a pseudo-periodicity of the reach by both methods, a condition which is clearly not fulfilled for all reaches of our dataset. But for the other rivers except Olivet (3) and Orgeval (6) reaches, there is no much improvement if we replace the total length with the assessed one. In this comparison, we found that the wavelengths extracted by the multivariate wavelet analysis are generally included in the variance intervals of the wavelengths found by the BDT. This was verified in all reaches except the Olivet River (3) where there is a big difference between the longitudinal spacings found by BDT and by wavelets. ~~bedforms instead of the number of pools and riffles for each method, and the dimensionless pool spacings instead of the reach wavelengths,~~

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~~6 – 3 – Discussion:~~

~~To provide an accurate assessment of each method, the variability of these results (Tables 5 and 6) must be discussed with some of the parameters in Table 1 and with the literature. In fact, the computation of the wavelength of each reach and the calculation of the numbers of bedforms remain the best morphological solution.~~

~~Moreover, we compare not only the dimensionless pool spacings λ^* and number of bedforms but also the Froude number Fr, the hydraulic radius Rh, the velocity/depth ratio, and the signal-to-noise ratio of each method. In this section, we choose the BDT results, which are closer to the other methods and to reality.~~

~~First, in the case of shorter lengths ℓ (the Avennelles reach), the index method underestimates the number of bedforms (four bedforms) and for longer lengths (the Olivet reach) the wavelet method also underestimates the number of bedforms (30 bedforms instead of 49 and 46 bedforms). Second, by examining the relation between the number of bedforms and λ^*, we find that when there is the same number of bedforms for the three methods (the Graulade and Orgeval reaches), with a deviation of one bedform at most, we find that the dimensionless pool spacings are very close as well, with a deviation of 0.3 at most. In the case of the Semme (2) and Ozanne (4) reaches, the number of bedforms are different for the three methods with a deviation of two bedforms at most, we find that dimensionless pool spacings vary from one method to another with a deviation of 0.6 at most. This explains why the three methods are almost equivalent and deviations represent only noise, which corresponds to parts ignored by a method and taken into account by another.~~

~~On the other hand, the Olivet (3) and Avennelles (5) reaches produce a large deviation in the wavelet and the index methods successively, and this is due to the methods themselves: the index method sweeps all the bedforms present in a studied length and mainly the higher ones while maintaining an accurate wavelength. However, the Avennelles reach shows that this method fails for small reaches where there are few bedforms and subsequently it does not give a good wavelength. Otherwise, the wavelet method is satisfied with few bedforms to estimate the wavelength of the reach.~~

Reaches	1: Graulade	2: Semme	3: Olivet	4: Ozanne	5: Avennelles	6: Orgeval
Total length L (m)	160.0	177.0	495.0	319.0	155.0	318.0
Assessed~~Studied~~ length ℓ (m)	67~~85~~.0	37~~98~~.0	251~~762~~.0	77~~190~~.0	60~~77~~.0	158~~161~~.0
$\lambda_{Wave,mean}$(m)~~Pools~~	21.54~~Riffles~~	21.74~~Pools~~	48.98~~Riffles~~	43.89~~Pools~~	26.59~~Riffles~~	48.29~~Pools~~ ~~Riffles~~
$\lambda_{BDT,mean}$(m)~~n_{Index}~~	23.67~~m_{Index}~~	25.33~~4~~	4 4 4 24.94	41.12~~25~~	33.63~~5~~	
$\lambda_{\ell,BDT,mean}$(m)	20.75	-	28.00	35.00	-	46.00
$\lambda^*_{Wav,mean}$~~n_{Wav}~~	~~m_{Wav}~~ 4 4 5.38	1.81~~5~~	8.16~~15~~ ~~15~~ ~~6~~ ~~5~~	3.66	2.954	
$\lambda^*_{BDT,mean}$~~n_{BDT1}~~	~~m_{BDT1}~~ 4 ~~3~~ 4 4 ~~23~~ ~~23~~ 5.92	2.11~~5~~	4.16	3.43		
$\lambda^*_{\ell,BDT,mean}$~~$n_{BDT2}$~~	~~m_{BDT2}~~ 4 ~~3~~ ~~3~~ ~~3~~ ~~21~~ ~~22~~ 5.19	-~~5~~	4.66	2.92~~3~~		
~~λ_{Index}(m)~~	~~23.3~~	~~27.5~~	~~32.3~~	~~40.6~~	~~56.0~~	~~50.8~~
$\lambda_{Wav,median}$(m)~~λ_{Wav}(m)~~	21.55~~23.3~~	21.84~~20.8~~	51.70~~55.7~~	43.49~~37.4~~	26.54~~24.4~~	48.78~~53.4~~
$\lambda_{BDT,median}$(m)~~λ_{BDT1}(m)~~	26.00~~22.3~~	21.25~~26.5~~	21.75~~34.3~~	36.50~~6~~	30.50~~26.0~~	39.00~~49.8~~
$\lambda_{\ell,BDT,median}$~~$\lambda_{BDT2}$(m)~~	20.75~~22.3~~	-~~35.5~~	23.50~~35.7~~	35.00~~36.6~~	-~~28.8~~	46.00~~49.8~~
$\lambda^*_{Wav,median}$~~λ^*_{Index}~~	5.39~~8~~	1.81~~2.3~~	8.62~~5.4~~	3.62~~4~~	~~6.~~2.95	4.88~~5.1~~
$\lambda^*_{BDT,median}$~~λ^*_{Wav}~~	6.5~~.8~~	1.77~~7~~	~~9.~~3.63	3.04~~1~~	3.39~~2.7~~	~~5.~~3.90
$\lambda^*_{\ell,BDT,median}$~~$\lambda^*_{BDT1}$~~	5.19~~6~~	-~~2.2~~	3.92~~5.7~~	2.92~~3.1~~	-~~2.9~~	4.60~~5.0~~
~~λ^*_{BDT2}~~	~~5.6~~	~~3.0~~	~~6.0~~	~~3.1~~	~~3.2~~	~~5.0~~
$\sigma(\lambda^*_{Wav,mean})$~~$\mu(A_m)_{Wav}$~~	0.09~~57~~	0.07~~30~~	0.70~~77~~	0.08~~44~~	0.04~~30~~	0.34~~81~~
$\sigma(\lambda^*_{BDT,mean})$~~$\mu(A_m)_{BDT}$~~	2.06~~0.80~~	0.82~~72~~	1.83~~0.95~~	1.56~~31~~	1.71~~0.49~~	1.91~~71~~
~~$\sigma(A_m)_{Wav}$~~ ~~$\sigma(A_m)_{BDT}$~~	~~0.08~~ ~~0.64~~	~~0.11~~ ~~0.84~~	~~0.29~~ ~~0.73~~	~~0.12~~ ~~0.76~~	~~0.04~~ ~~0.58~~	~~0.18~~ ~~1.77~~
$\sigma(\lambda^*_{\ell,BDT,mean})$~~$SNR_{Wav}$~~	2.21~~7.50~~	-~~2.68~~	2.30~~70~~	-~~3.55~~	-~~7.91~~	0.71~~4.58~~
~~SNR_{BDT}~~	~~1.26~~	~~0.86~~	~~1.34~~	~~1.73~~	~~0.85~~	~~0.97~~

Table 5. Results of BDT and the multivariate wavelet methods for all reaches. $\lambda_{meth,mean}$ is the mean wavelength using one of the methods (for BDT, it used on total length and on the assessed one ℓ). $\lambda_{meth,median}$ is the median, and $\lambda^*_{meth,mean}$ is the mean longitudinal spacing, $\lambda^*_{meth,median}$ is the median, and $\sigma(\lambda^*_{meth,mean})$ is the standard deviation related to the longitudinal spacing. (-) means that we find only one longitudinal spacing which is the mean and the median and there is no standard deviation.

5 – Discussion:

In this study, we consider the BDT method as a benchmark method. We do not consider a specific method to be the "true" or "reference" one, we only apply these methods to have a general idea on the uncertainties in the identification of morphological units. This method was chosen not because it is the 'best' method for pool-riffle identification, but because it does not use thresholds (except for the tolerance T which does not depend on field data). It means that it does not require a preliminary calibration of thresholds on velocity, hydraulic radius, etc. on an independent reach (e.g., Wyrick and Pasternack, 2014 ; Hauer et al., 2009). These thresholds vary from one reach to another and according to characteristics of each river. For this reason, we didn't compare our method with threshold methods on this dataset. In contrast, the results of the longitudinal spacing intervals will be compared with literature.

For a long time, researchers have found common interval of longitudinal spacings that vary between 5 and 7 times the channel width (Leopold et al., 1964; Keller, 1972; Richards, 1976; Gregory et al., 1994). Keller (1972) found that the median is less and varies between 3 and 5 the channel width. O'Neil and Abrahams (1984), using BDT method, found the same results but with a median close to 3 the channel width and this

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value can vary according to the tolerance T. Carling and Orr (2000) found lower values than before at about 3W. Recent studies (e.g., Wyrick and Pasternack, 2014) have calculated the longitudinal spacing of six morphological units using 2D identification methods. The average of these pool and riffle spacings are, respectively, 3.3 and 4.3 the channel width, which is less than the commonly accepted values of 5–7 W.

In this study, the longitudinal spacing vary in the mean and the median from ~1.8 to 8.6~~**Table 5.** Summary of results: n is the number of pools and m is the number of riffles, λ_{Index} and λ_{BDT} are the average between the wavelengths calculated between two pools and between two riffles, BDT1 means BDT for T = S$_D$ and BDT2 means BDT for T = 2S$_D$, λ^* is calculated by $\frac{\lambda}{w_{bf}}$, and w_{bf} is taken from Table 1. The amplitude is calculated in the case of BDT for T = S$_D$ and it is the difference between two successive extremums, $\mu(A_m)_{BDT}$ is their mean, $\sigma(A_m)_{BDT}$ their standard deviation, and SNR_{BDT} is the signal to noise ratio, which is the ratio of the signal's mean to standard deviation. However, the mean amplitude of the wavelet method is calculated using Eq. (21).~~

~~The Froude number in Table 6 varies in pools from 0.01 and 0.02 (the Olivet) to 0.30 (the Graulade), with an average of 0.11 and 0.12 successively for the index and wavelet methods. Otherwise in riffles, it varies from 0.04 and 0.03 (the Olivet) to 0.37 and 0.36 (the Graulade), with an average of 0.23 and 0.20 successively for the index and wavelet methods. Furthermore, The hydraulic radius varies in pools from 0.18 (the Graulade) to 0.54 and 0.50 (the Olivet), with an average of 0.33 and 0.29 successively for the index and wavelet methods. However, it varies in riffles from 0.11 (the Avennelles) and 0.15 (the Graulade, the Ozanne, and the Avennelles) to 0.37 and 0.50 (Olivet), with averages of 0.19 and 0.23 successively for the index and wavelet methods. The velocity/depth ratio varies in pools from 0.03 and 0.06 (the Olivet) to 1.29 and 1.28 (the Graulade) with averages of 0.42 and 0.55 successively for the index and wavelet methods. In riffles, it varies from 0.15 and 0.09 (the Olivet) to 2.87 and 2.04 (the Avennelles), with averages of 1.31 and 1.12 successively for the index and wavelet methods.~~

~~These results support Allen's classification for pools for all reaches except the Graulade (1), which have a short length and high slope (0.0125 m/m). For riffles, they support the classification only for the Graulade (1) and Avennelles (5) reaches.~~

~~For all reaches, the dimensionless pool spacings vary from 1.7 to 9.3, with an average spacing 4.5~~ times the bankfull width, supporting the conclusion of Carling and Orr (2000) that pools are spaced approximately three to seven times the channel width. However, the quoted longitudinal~~pool~~ spacing relationships should be considered in the context that the bankfull width and spacing distance are inherently variable even for short length reaches. To illustrate this inherent variability, we found the example of Keller and Melhorn (1978) where the pool-pool spacing values ranged from 1.5 to 23.3 channel widths, with an overall mean of 5.9 (Gregory et al., 1994; Knighton, 2014). This variability in longitudinal spacing is probably related to a short assessed length, a small number of cross-sections surveyed, or other factors such as geology, bank characteristics (cohesion), grain size of the river bed, artificial channel modifications, etc.

We worked with a dataset that contains cross-sections spaced 0.46 to 2.9 times bankfull width. Other studies have used much shorter spacings (e.g., Pasternack et al., 2018b; Legleiter, 2014b) to identify morphological units. Of course, the larger the number of cross-sections, the more robust the identified correlations will be. In addition, we worked with irregularly spaced cross-sections, which will normally lead to biases in the results. Despite this, the "biased" placement does not impairs the overall methodology. This methodology has provided good results in terms of longitudinal spacings and therefore it can be applied for a shorter cross-section spacings to clearly identify these alternate morphologies. The short lengths we found raise

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questions about the naturality of the rivers. In our case, the rivers are subject to artificial modifications (e.g., bridges, weirs) and rehabilitations, which will have a significant impact on the hydro-morphological parameters (width, depth, meandering, etc.). This can have a very important impact on the identification of pseudo-periods.

The wavelet ridge analysis is powerful in identifying pseudo-periods, amplitude and phase while respecting the correlations between parameters. We can thus identify alternating morphological units in a more objective way in terms of frequency/wavenumber. From this extracted common wavelength using the flow parameters, it is possible to represent the topography continuously.

On the other hand, it represents drawbacks compared to other methods. First, the cone of influence that ignores a large part of the river and sometimes biases the results (in the case of the Graulade (1) and Semme (2) reaches) in the case of small total lengths. It is the region of the wavelet spectrum in which edge effects become important. We can say the same thing for reach length and number of morphological units as for the number of cross-sections: the larger it is, the more robust the results will be, and the smaller the relative portion of "unassessed length" will be. Still, the method remains a powerful tool for non-stationary analysis. Another problem is the amplitude which is sometimes overestimated in some regions of the topography. We visualized this in several cases in our study, since we used the Neperian logarithm to avoid negative values and therefore the inverse function (exponential) will give slightly larger values. However, this does not bias the identified wavelength of the reach.

6 – Conclusions:

In this study, we present an automatic procedure based on Wavelet Ridge extraction to identify some characteristics of alternating morphological units (MU), such as their longitudinal spacing and amplitude. The method does not rely on any a priori thresholds to identify MU sequences. It was applied to six rivers with a maximum length of 500 meters. We chose to work with classical hydro-morphological variables (velocity, hydraulic radius, bed shear stress) in addition to the local channel direction angle that evaluates the impact of river sinuosity in the determination of the wavelength.

On the overall, identified wavelength are consistent with values of the literature (mean in 3-7 w_{bf}). The use of a multivariate approach yields more robust results than the univariate approaches, by ensuring a consistent covariance of flow variables in the pseudo-periodic behavior.

Given the short length of several reaches, the relatively small number of cross-sections for each reach, and the possible impacts of artificial modifications, this paper is mainly a proof-of-concept of the wavelet approach. It does not preclude the long-term possibility of extending the work to other rivers with other types of MUs, other longer reaches with a large number of cross-sections.

~~The comparison shows higher amplitudes and standard deviations for the BDT than the wavelet method, which yields a higher signal-to-noise ratio $SNR = \frac{\mu(A_m)}{\sigma(A_m)}$. These higher values mean good wavelet performance to extract more useful information than the noise.~~

~~Reaches~~	~~1: Graulade~~		~~2: Semme~~		~~3: Olivet~~		~~4: Ozanne~~		~~5: Avennelles~~		~~6: Orgeval~~		~~Mean~~	
~~Variables~~	~~P~~	~~R~~	~~P~~	~~R~~	~~P~~	~~R~~	~~P~~	~~R~~	~~P~~	~~R~~	~~P~~	~~R~~	~~P~~	~~R~~
~~Fr_{index}~~	~~0.30~~	~~0.37~~	~~0.09~~	~~0.12~~	~~0.01~~	~~0.04~~	~~0.08~~	~~0.24~~	~~0.10~~	~~0.36~~	~~0.06~~	~~0.22~~	~~0.11~~	~~0.23~~
~~Fr_{wav}~~	~~0.30~~	~~0.36~~	~~0.10~~	~~0.11~~	~~0.02~~	~~0.03~~	~~0.10~~	~~0.23~~	~~0.12~~	~~0.27~~	~~0.10~~	~~0.19~~	~~0.12~~	~~0.20~~

~~Rh_{index}~~	~~0.18~~	~~0.15~~	~~0.35~~	~~0.26~~	~~0.54~~	~~0.37~~	~~0.29~~	~~0.14~~	~~0.23~~	~~0.11~~	~~0.42~~	~~0.19~~	~~0.33~~	~~0.19~~
~~Rh_{wav}~~	~~0.18~~	~~0.15~~	~~0.32~~	~~0.30~~	~~0.50~~	~~0.44~~	~~0.24~~	~~0.15~~	~~0.20~~	~~0.15~~	~~0.33~~	~~0.23~~	~~0.29~~	~~0.23~~
~~u/y_{index}~~	~~1.29~~	~~1.87~~	~~0.29~~	~~0.44~~	~~0.03~~	~~0.15~~	~~0.25~~	~~1.17~~	~~0.40~~	~~2.87~~	~~0.23~~	~~1.28~~	~~0.42~~	~~1.31~~
~~u/y_{wav}~~	~~1.28~~	~~1.92~~	~~0.34~~	~~0.44~~	~~0.06~~	~~0.09~~	~~0.36~~	~~1.09~~	~~0.68~~	~~2.04~~	~~0.57~~	~~1.06~~	~~0.55~~	~~1.12~~

~~**Table 6.** Hydraulic variables results for all reaches for the Froude Number Fr, the hydraulic radius Rh, and the ratio velocity/ depth u/y, these variables are averaged on the number of pools and riffles for each reach.~~

~~To conclude, pools and riffles have a subjective definition, and this study is a step towards a more quantitative approach. On the one hand, the wavelet method identifies bedforms and extracts their wavelength by focusing on the most revealing part of the reach, which contains all the reach's information, but what differentiates this method from the others is its capability to extract the pool-riffle amplitudes. It could be extended in a multivariate case with a quantitative approach by crossing several variables. On the other hand, the index method suggests identifying all the major and minor bed profile undulations, but it cannot extrapolate a wavelength to all the reaches based on only a small part of this reach.~~

Appendix A: List of symbols

$A_{i,mod}$:	Signal amplitude of the shape of the modeled variable number i
A(x):~~:~~	Cross-section area~~Wetted surface (m^2)~~
A_m:	Signal amplitude of the shape
$\cos(\theta)$:	Cosine of local channel direction angle
$\cos(\theta)_{mod}$:	Modeled cosine of local channel direction angle
f:	Space series function~~ (m)~~
f_i:~~Fr:~~	Measured space series function~~Froude~~ number i
$f_{i,mod}$:	Modeled space series function number i with multivariate wavelet analysis
f_{mod}:	Modeled variable with the univariate wavelet analysis
g:	Acceleration due to gravity and its value is 9.81 m.s^{-2}
J~~I~~:	Energy slope (m.m^{-1})~~Index function~~
~~I_W:~~	~~Identified signal that represents alternating pools and riffles~~
k(x):~~:~~	Wavenumber (rad.m^{-1})
K(x):~~:~~	Local wavenumber that corresponds to the maximum variance of the signal (rad.m^{-1})
~~Ks:~~	~~Strickler coefficient~~
~~k_ψ:~~	~~Peak wavenumber, which is the spatial frequency domain that has a maximum amplitude (rad.m^{-1})~~
ℓ:	K(x) support (m)
L:	Total reach length (m)
~~$\ell[a;b]$:~~	~~Length of [a; b] (m)~~
N:	Number of total chosen variables~~selected descriptors~~
n~~ and m~~	Manning's roughness coefficient~~Number of pools and riffles identified, respectively, by the wavelet method~~
~~n' and m'~~	~~Number of pools and riffles identified, respectively, by the index method~~
~~p:~~	~~Normalized descriptor~~
~~p_i:~~	~~Descriptor's value~~
~~$\tilde{p}_i^W$:~~	~~Interval of the abscissa of the ith pool identified by the wavelet method~~
~~$\tilde{p}_j^I$:~~	~~Interval of the abscissa of the jth pool identified by the index method~~
~~p_m:~~	~~Descriptor's mean~~
P(x):~~:~~	Wetted perimeter~~ (m)~~
~~$\tilde{P}_I$:~~	~~Pool interval identified by the index method~~
~~$\tilde{P}_W$:~~	~~Pool interval identified by the wavelet method~~

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~~Q:~~	~~Reach discharge (m3.s^{-1})~~
Q_{min}:	Minimum discharge modeled (m3.s^{-1})
~~Q_{max}:~~	~~Maximum discharge modeled (m3.s^{-1})~~
~~$\tilde{r}_i^W$:~~	~~Interval of the abscissa of the ith riffle identified by the wavelet method~~
~~$\tilde{r}_j^I$:~~	~~Interval of the abscissa of the jth riffle identified by the index method~~
R(x,s) or R(x,k) or R	Absolute value or modulus of the wavelet transform at a position x and with a scale s or wavenumber k
R_h	Hydraulic radius (m)
$R_{h,mod}$~~$\tilde{R}_I$:~~	Modeled hydraulic radius (m)~~Pool interval identified by the index method~~
~~$\tilde{R}_W$:~~	~~Riffle interval identified by the wavelet method~~
s:	Dilation or scale factor
S:	Reach slope (m.~~/~~m^{-1})
S_D~~:~~	Standard deviation of the bed elevation diffrence series (m)
T:	Tolerance value, which is the minimum absolute value of the cumulative elevation change required for the identification of pools and riffles (m)
u(x) or v(x)~~:~~	Velocity (m.s^{-1})
v_{mod}~~u_m:~~	Modeled~~Mean~~ velocity (m.s^{-1})
v_{obs}	Mesured velocity (m.s^{-1})
w(x):~~:~~	Reach width in the x abscissa (m)
w_{bf}:	Reach bankfull width (m)
w_m	Mean width (m)
x:	Translation factor in the wavelet transform or the abscissa position (m)
$y = y_{max}$:	Water depth measured from the the talweg elevation $y = z_{ws} - z$ (m)
y_m:	Mean depth (m)
~~y_{max}:~~	~~Maximum depth (m)~~
z or $z_{t,Obs}$:	Measured bed~~Bed~~ elevation or talweg elevation (m)
$z_{t,Uni}$:	Modeled bed elevation using the univariate wavelet analysis (m)
$z_{t,Multi}$:	Modeled bed elevation using the Multivariate wavelet analysis (m)
z_{ws}:	Water surface elevation measured from the 0NGF (m)
α:	Fourier factor associated with the wavelet (m.rad^{-1})
β:	Dimensionless frequency taken to be 6 recommended by Torrence and Compo (1998)
λ:	Reach wavelength (m)
λ^*:	Typical pool (riffle) spacing or dimensionless reach wavelength or longitudinal spacing
ρ:~~$\mu()$:~~	Water density (997kg/m^3)~~Variable mean~~
$\sigma(w)$:	Standard deviation of the width along the reach (m)
$\sigma()$:~~(p_i):~~	Standard~~Descriptor's standard~~ deviation
$\tau_b(x)$:	Bed shear stress in the x abscissa (Pa)
$\tau_{b,mod}(x)$:	Modeled bed shear stress in the x abscissa (Pa)
$\theta(x)$:	local channel direction angle which is the local angular deviation of the channel direction from a lower-frequency curve (degrees)
Φ:	Corresponding phase at the position x and the wavenumber K with $\Phi(x) = \phi(x, K(x))$ (rad)
Φ_i:	Phase at the position x and the wavenumber K for the variable number i
$\phi(x,s)$ or $\phi(x,k)$ or ϕ:	Phase or argument at a position x and with a scale s or wavenumber k (rad)
ϕ_i:	Phase of the variable number i
ψ:	Mother wavelet function
$\psi_{s,x}$:	Daughter wavelet function

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η:	Dimensionless position parameter
~~1:~~	~~Heaviside step function~~
~~$\mathbb{R}_+^*$~~	~~Positive real numbers~~
$\mathbb{C}$:	Complex numbers
W[f](x,s):	Continuous wavelet transform of f(x) with the wavelet ψ

Appendix B: Mathematical calculus for the wavelet transform

1 – The univariate case

The conjugate form of the mother wavelet is:

$$\psi^*(\eta) = \pi^{-\frac{1}{4}} e^{-i\beta\eta - \frac{\eta^2}{2}} \qquad \text{(B1)}$$

Its~~whose~~ derivative in relation to the mute variable η is:

$$\begin{aligned}\psi^{*\prime}(\eta) &= -\pi^{-\frac{1}{4}}(i\beta + \eta)e^{-i\beta\eta - \frac{\eta^2}{2}} \\ &= -(i\beta + \eta)\psi^*(\eta)\end{aligned} \qquad \text{(B2)}$$

In ~~the wavelet ridge analysis~~ section 3 - 1, η is a mute integration variable and x appears only in the argument $\alpha k(\xi - x)$ of the function ψ^*. By applying the derivation formula of a composite function, the derivative of the wavelet transform is expressed by:

$$\begin{aligned}&\frac{\partial}{\partial x} W[f(x)](x,k) = \sqrt{\alpha k}\int_{-\infty}^{+\infty} f(\eta)\frac{\partial}{\partial x}\left[\psi^*\big(\alpha k(\eta - x)\big)\right]d\eta \\ &= \sqrt{\alpha k}\int_{-\infty}^{+\infty} f(\eta)(-\alpha k)\psi^{*\prime}\big(\alpha k(\eta - x)\big)d\eta \\ &= (\alpha k)\sqrt{\alpha k}\int_{-\infty}^{+\infty} f(\eta)\big(i\beta + \alpha k(\eta - x)\big)\psi^*\big(\alpha k(\eta - x)\big)d\eta \\ &= (\alpha k)\sqrt{\alpha k}\int_{-\infty}^{+\infty} [(i\beta - \alpha k x)f(\eta) + \alpha k\eta f(\eta)]\psi^*\big(\alpha k(\eta - x)\big)d\eta \\ &= (\alpha k)(i\beta - \alpha k x)W[f(x)](x,k) + (\alpha k)^2 W[xf(x)](x,k)\end{aligned} \qquad \text{(B3)}$$

On the other hand, we have:

$$\begin{aligned}&\frac{\partial}{\partial x} W[f(x)](x,k) = \frac{\partial}{\partial x}\left(R(x,k)e^{i\phi(x,k)}\right) \\ &= \left[\frac{1}{R(x,k)}\frac{\partial R(x,k)}{\partial x} + i\frac{\partial \phi(x,k)}{\partial x}\right]R(x,k)e^{i\phi(x,k)}\end{aligned} \qquad \text{(B4)}$$

$$\begin{aligned}&\frac{\partial}{\partial x}\mathrm{Re}\big(\ln W[f(x)](x,k)\big) = \frac{1}{R(x,k)}\frac{\partial R(x,k)}{\partial x} = \mathrm{Re}\left(\frac{1}{W[f(x)](x,k)}\frac{\partial}{\partial x}W[f(x)](x,k)\right) \\ &\frac{\partial}{\partial x}\mathrm{Im}\big(\ln W[f(x)](x,k)\big) = \frac{\partial \phi(x,k)}{\partial x} = \mathrm{Im}\left(\frac{1}{W[f(x)](x,k)}\frac{\partial}{\partial x}W[f(x)](x,k)\right)\end{aligned} \qquad \text{(B5)}$$

Finally:

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$$\begin{aligned}\frac{\partial\phi(x,k)}{\partial x} &= \mathrm{Im}\left((\alpha k)(i\beta-\alpha kx)+(\alpha k)^2\frac{W[xf(x)](x,k)}{W[f(x)](x,k)}\right)\\ \frac{\partial\phi(x,k)}{\partial x} &= (\alpha k)\beta+(\alpha k)^2\mathrm{Im}\left(\frac{W[xf(x)](x,k)}{W[f(x)](x,k)}\right)\end{aligned} \tag{B6}$$

The previous expression numerically avoids the derivative of the function $\phi(x,k)$, which varies quickly for large wavenumbers.

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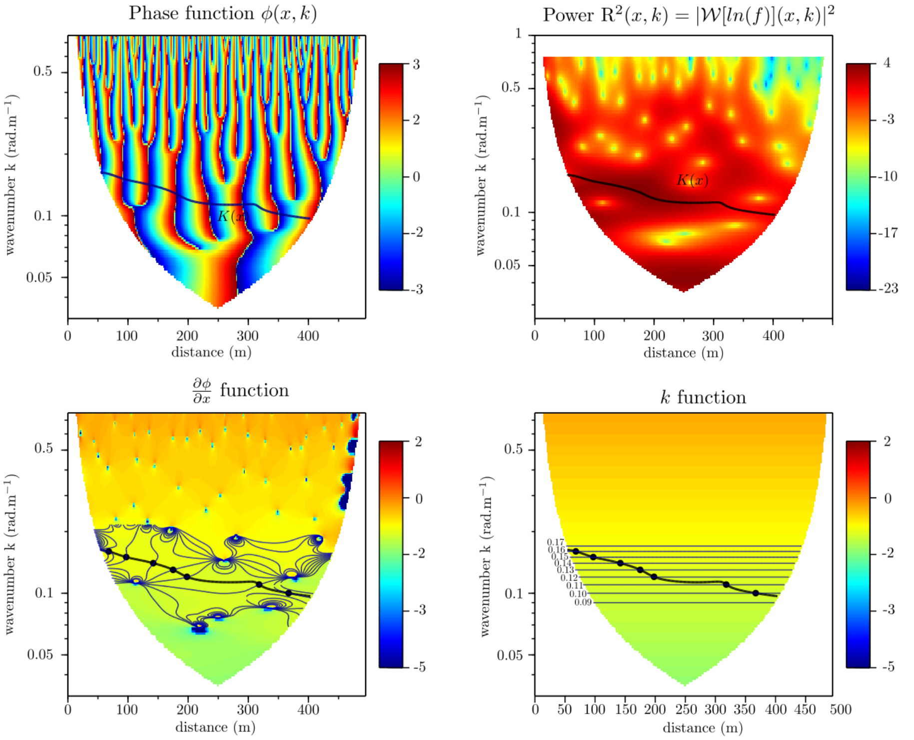

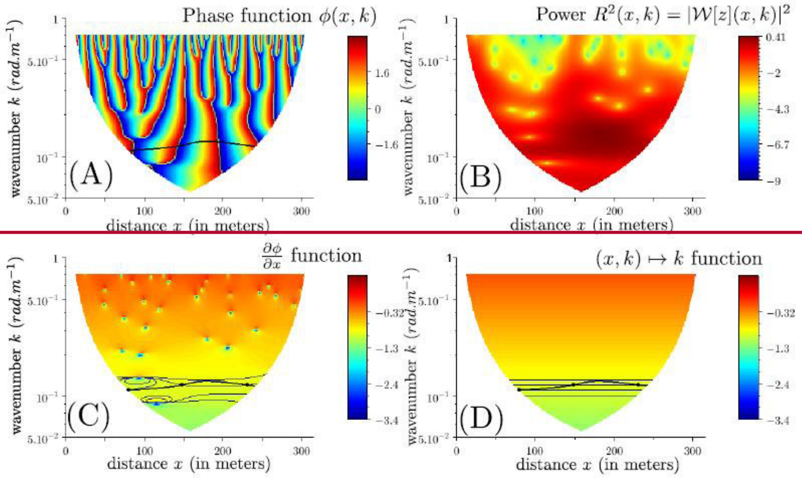

Figure B1. Steps of determining the local wavenumber K(x) using the wavelet univariate ridge analysis~~transform~~ of the the velocity of the Olivet (3) reach~~bed elevation z~~, represented in the four panels. (A) The phase function $\phi(x,k)$; (B) the power's cone of influence of the wavelet to characterize the region where there is a maximum variability of the velocity in Neperian logarithm; (C) the function $\frac{\partial\phi(x,k)}{\partial x}$; (D) the function k.

2 – The multivariate case

In the multivariate case, we should resolve the Eq. 20 which contain three derivatives to compute. The first one is already done in the univariate case which is:

$$\frac{\partial\phi_i(x,k)}{\partial x} = (\alpha k)\beta + (\alpha k)^2 \mathrm{Im}\left(\frac{W[xf_i(x)]}{W[f_i(x)]}\right) \tag{B7}$$

The second one is the computation of $\frac{\partial^2\phi_i(x,k)}{\partial k \partial x}$:

$$\frac{\partial^2\phi_i(x,k)}{\partial k \partial x} = \alpha\beta + 2\alpha^2 k \mathrm{Im}\left(\frac{W[xf_i(x)]}{W[f_i(x)]}\right) + (\alpha k)^2 \mathrm{Im}\left(\frac{\partial}{\partial k}\left(\frac{W[xf_i(x)]}{W[f_i(x)]}\right)\right) \tag{B8}$$

For that we should develop $\frac{\partial}{\partial k}\left(\frac{W[xf_i(x)]}{W[f_i(x)]}\right)$:

$$\frac{\partial}{\partial k}\left(\frac{W[xf_i(x)]}{W[f_i(x)]}\right) = \frac{1}{W[f_i(x)]}\frac{\partial W[xf_i(x)]}{\partial k} - \frac{W[xf_i(x)]}{(W[f_i(x)])^2}\frac{\partial W[f_i(x)]}{\partial k}$$

We calculate each derivative:

$$\frac{\partial W[f_i(x)]}{\partial k} = \left(\frac{1}{\sqrt{k}}\frac{\partial\sqrt{k}}{\partial k}\right) W[f_i(x)] + \sqrt{\alpha k}\int_{-\infty}^{+\infty} f(\eta)\frac{\partial}{\partial k}\left[\psi^*\left(\alpha k(\eta - x)\right)\right] d\eta$$

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$$= \left(\frac{1}{2k}\right) W[f_i(x)] + \sqrt{\alpha k} \int_{-\infty}^{+\infty} f(\eta)\alpha(\eta - x)\psi^{*\prime}\big(\alpha k(\eta - x)\big)d\eta$$

$$= \left(\frac{1}{2k}\right) W[f_i(x)] + \sqrt{\alpha k} \int_{-\infty}^{+\infty} f(\eta)\alpha(\eta - x)\big(i\beta + \alpha k(\eta - x)\big)\psi^{*}\big(\alpha k(\eta - x)\big)d\eta$$

$$= \left(\frac{1}{2k}\right) W[f_i(x)] + \sqrt{\alpha k} \int_{-\infty}^{+\infty} [(i\beta - \alpha^2 k x^2) + (-i\beta\alpha + 2\alpha^2 k x)\eta - (\alpha^2 k)\eta^2] f(\eta)\psi^{*}\big(\alpha k(\eta - x)\big)d\eta$$

$$= \left(\frac{1}{2k} - \alpha^2 k x^2 + i\beta\alpha x\right) W[f_i(x)] + (2\alpha^2 k x - i\beta\alpha) W[x f_i(x)] - (\alpha^2 k) W[x^2 f_i(x)]$$

We find a general formulation with p=0…N:

$$\frac{\partial W[x^p f_i(x)]}{\partial k} = \left(\frac{1}{2k} - \alpha^2 k x^2 + i\beta\alpha x\right) W[x^p f_i(x)] + (2\alpha^2 k x - i\beta\alpha) W[x^{p+1} f_i(x)] - (\alpha^2 k) W[x^{p+2} f_i(x)]$$

The third one is the computation of $\frac{\partial^3 \phi_i(x,k)}{\partial k^2 \partial x}$:

$$\frac{\partial^3 \phi_i(x,k)}{\partial k^2 \partial x} = 2\alpha^2 \mathrm{Im}\left(\frac{W[x f_i(x)]}{W[f_i(x)]}\right) + 4\alpha^2 k \mathrm{Im}\left(\frac{\partial}{\partial k}\left(\frac{W[x f_i(x)]}{W[f_i(x)]}\right)\right) + (\alpha k)^2 \mathrm{Im}\left(\frac{\partial^2}{\partial k^2}\left(\frac{W[x f_i(x)]}{W[f_i(x)]}\right)\right) \qquad \text{(B9)}$$

$$\frac{\partial^3 \phi_i(x,k)}{\partial k^2 \partial x} = 2\alpha^2 \mathrm{Im}\left(\frac{W[x f_i(x)]}{W[f_i(x)]}\right) + 4\alpha^2 k \mathrm{Im}\left(\frac{\partial}{\partial k}\left(\frac{W[x f_i(x)]}{W[f_i(x)]}\right)\right) + (\alpha k)^2 \mathrm{Im}\left(\frac{\partial^2}{\partial k^2}\left(\frac{W[x f_i(x)]}{W[f_i(x)]}\right)\right)$$

With :

$$\frac{\partial^2}{\partial k^2}\left(\frac{W[x f_i(x)]}{W[f_i(x)]}\right) = \frac{1}{W[f_i(x)]}\frac{\partial^2 W[x f_i(x)]}{\partial k^2} - \frac{W[x f_i(x)]}{(W[f_i(x)])^2}\frac{\partial^2 W[f_i(x)]}{\partial k^2} - \frac{2}{(W[f_i(x)])^2}\frac{\partial W[f_i(x)]}{\partial k}\frac{\partial W[x f_i(x)]}{\partial k}$$

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Supplementary materials:

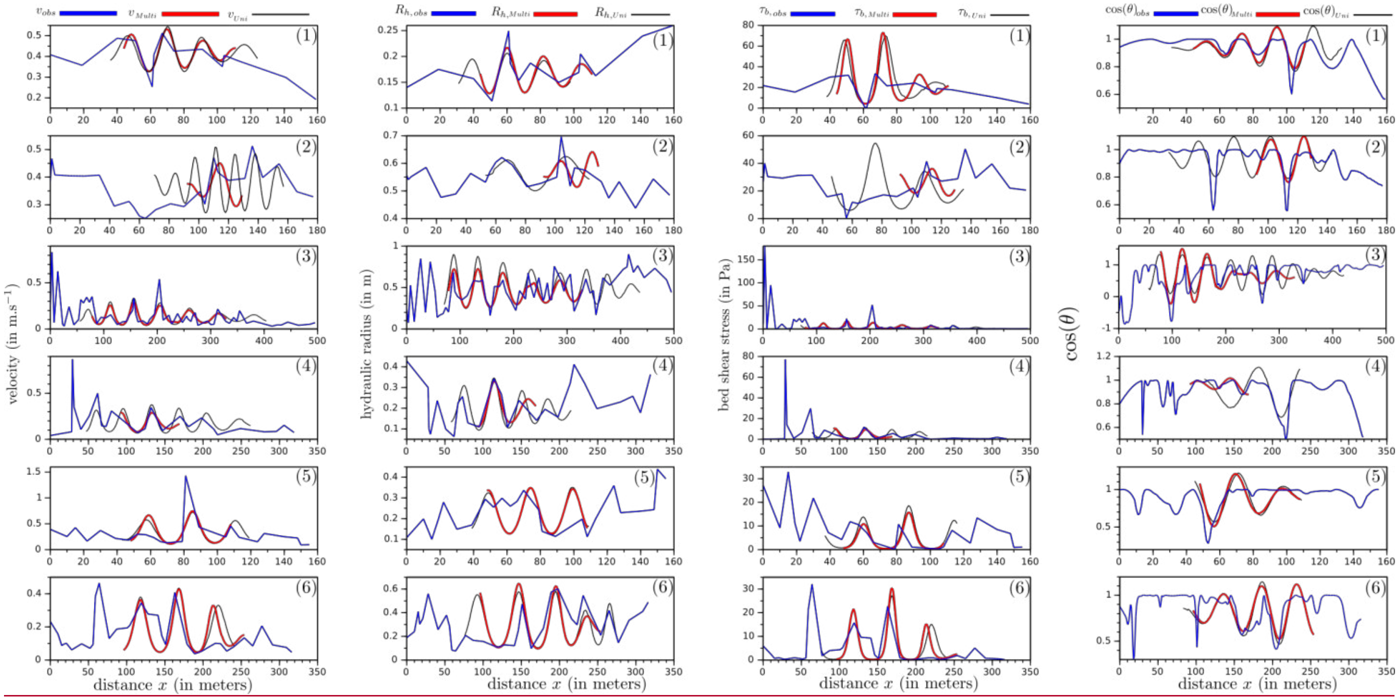

Figure S1: Comparison between the univariate and the multivariate results for the six reaches (from 1 to 6) and using the four variables (velocity, hydraulic radius, bed shear stress, and cosine of local channel direction angle).

Mis en forme : Gauche : 2,5 cm, Droite : 2,5 cm, Haut : 2,5 cm, Bas : 2,5 cm, Largeur : 27,94 cm, Hauteur : 21,59 cm, Distance de l'en-tête par rapport au bord : 1,25 cm, Distance du bas de page par rapport au bord : 1,25 cm

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