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# Meander Statistics Toolbox (MStaT): A toolbox for geometry characterization of bends in large meandering channels

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ABSTRACT

This contribution presents MStaT, a wavelet-based open-source software developed to provide a detailed characterization of large meandering river morphodynamics. MStaT integrates three independent modules: (i) meandering morphometrics module; (ii) migration module; and (iii) confluence module. MStaT delivers a short and medium-term framework to analyze the river centerline and valley-meandering channel interrelationship at low computational cost. It provides quantitative information on the spatial distribution of the arc-wavelength, migration rates, cutoffs events, and tributary channels influences. Data are presented through a user-friendly graphical user interface that makes the output interpretation easier, and that is freely available to the communities of river morphodynamics scientists and engineers.



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| Support email for questions | ldominguez@fich.unl.edu.ar; ldominguezruben@gmail.com |

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| Legal Software License | *GPL-3.0* |
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| If available, link to user manual - if formally published include a reference to the publication in the reference list | https://github.com/ldominguezruben/meanderstatisticstoolbox/tree/main/usermanual |
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## 1. Introduction

Meandering channels represent one of the most complexes yet common channel patterns among alluvial rivers [1]. One of

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the main characteristics of these rivers is the dynamic interaction between the river channel and the surrounding floodplain, where the planform dynamics of the meandering channels play a key role in the channel sedimentation and erosion processes [2], as well as in hydrological and ecological processes [3,4]. Thus, scientific knowledge of such processes is important to understand the functions of the river–floodplain ecosystem, which is subjected to water quality degrading, river–floodplain ecological connectivity disruption, and aquatic-habitat health and diversity decrease [5,6]. Moreover, the dynamics of meandering river channels is relevant to river engineers and managers, who focus on flood control, navigation, and the protection of land and infrastructure.

The recent increase in accessibility to geographic information systems (GIS) has led to the emergence of the 'remote sensing of rivers' as a means to study fluvial geomorphology and to characterize large meandering rivers [7]. Numerous efforts have been made to characterize large planforms dynamics using satellite images on GIS platforms [8–12], as well as on MATLAB and Python platforms [13–15]. However, these models have been developed with no graphical user interface (GUI), which makes it difficult for users with no programming knowledge to use it. Moreover, the classical scheme of meandering planform characterization, which uses discrete geometric parameters such as sinuosity, arc-wavelength, and amplitude, is not able to fully capture the complex nature of, for example, the valley-channel interrelationship of the intricate curvatures widely observed in environments with high degree of morphodynamic changes such as the Amazon river basin [16].

To improve the characterization of the geometry of meanders, recent studies have applied mathematical techniques, such as continuous wavelet transform (CWT) and wavelet principal component analysis (WPCA), to meander planform geometry analysis [16]. The CWT identifies dominant wavelength, whose spatial distribution provides useful insights into the wave-like geometry such as the meander planform. The WPCA allows the decomposition of the planimetric signal, which provides a medium-term framework for analyzing meandering dynamics processes [16]. These techniques have also been applied to the characterization of the wave-like forms at large spatial extent in various environmental scenes [17–22].

This paper presents a summary about of the technical background, functionalities, and applications of examples of Meander Statistics Toolbox (MStaT), a MATLAB-based platform with a user-friendly GUI for meander planform geometry and dynamics analysis. MStaT performs a comprehensive analysis by means of classical measurements, such as river centerline sinuosity and lateral migration rate, as well as the CWT and the WPCA. The paper is structured as follows: Section 2 provides a brief introduction to the wavelet theory applied in this work. Section 3 describes the software architecture and its main functionalities. Section 4 shows an example of its implementation. Section 5 discusses the impact that MStaT brings about. Section 6 provides a summary and a conclusion about this contribution.

## 2. Background

In analyzing the planform of a meandering river, two centerlines are typically identified: the river centerline (RC) and the valley centerline (VC). The valley is defined as the area within which a meandering river can move freely [16]. The time frame for RC changes is relatively short, usually from decades to centuries, and it is associated with the time frame of lateral meander migration. On the other hand, the time frame for the VC is long, and it is typically considered as the geological time frame. Previous research has presented a new time frame termed 'mean center' (MC), which is approximated as the centerline of meander-belt, and it is strongly affected by meander cutoff events, rather than by the lateral migrations of the channel [16]. Thus, the MC represents the medium-term frame, and it provides deeper insight into meandering planforms [16]. MStaT employs the CWT to characterize the short-term frame (i.e. RC). Using the CWT, a temporal–spatial series is transformed into a 2D time-spatial frequency representation [16,19].

The WPCA plays a key role in signal decomposition for the obtaining of the MC [16]. This analysis requires two input parameters: the discrete wavelet function and the level $J$ (or wavelet coefficient) at which the planimetric signal is filtered, with $J = 1$ representing the non-filtered original signal. The signal is analyzed at altered frequencies with different resolutions to be decomposed. Daubechies algorithm [23] is used to obtain the wavelet coefficient. Obtaining an appropriate value for filtering level $J$ requires a comparison between the resulting MC and the observed data. Previous work has indicated that a lower $J$ value gives better results for confined meandering rivers [16]. For further details on the WPCA methodology, please refer to [16,24].

## 3. Software framework

### 3.1. Software architecture

Three independent modules are integrated into MStaT; meandering morphometrics module (M1), migration module (M2), and confluence module (M3) (Fig. 1). Each module can be executed (data input and outputs) independently, although M2 and M3 are accessed through M1. It should be noted that all modules access to the CWT analysis for the execution of the wavelet analysis.

The workflow is as follows: first, the user is required to select the module to be run. Then, the RC file, which is drawn from upstream to downstream, is selected and the average channel width ($W$) is entered. The $W$ should be selected carefully, as it defines the sampling spacing of the RC discretization and, consequently, it affects the analysis. Large sampling spacing results in a misrepresentation of the RC, while small sampling spacing results in an increase in computational cost and noisy output. In the case of M2, an RC from a different time and the corresponding elapsed time (in years) are additionally required. For M3, at least two RCs, one for the main channel and the others for tributaries, and corresponding average channel widths are required. The RC can be provided in ASCII text (.txt), Excel (.xls and .xlsx) or Keyhole Markup Language (.kml) with $x$ and $y$ georeferencing points in a project coordinate system (e.g. easting and northing). It should be noted that $x$ and $y$ points are treated as imaginary numbers so that the real part refers to East and the imaginary referring to North [16].

Lastly, the results are summarized in tables and figures. The former can be exported as plain texts (.dat) and Excel (.xls and .xlsx), and the latter can be exported as images (.jpg, .tif, and .png), respectively. The user can also export the results in .kml format if the input RC is provided in .kml. The exported Excel file and georeferenced results allow for the development of a web-database of the different analyzed channels (an application case of MStaT can be found at http://www.dancingrivers.com/). Additionally, MStaT allows the background image to be incorporated. However, the background image must be georeferenced and provided in GeoTIFF format.

### 3.2. Software functionalities

Once the RC and its $W$ are specified, MStaT converts the geographical coordinates of the RC into local coordinates (i.e. longitudinal and normal coordinates $s$ and $n$, respectively). To compute the curvature fluctuations, an algorithm by [25] that utilizes cubic

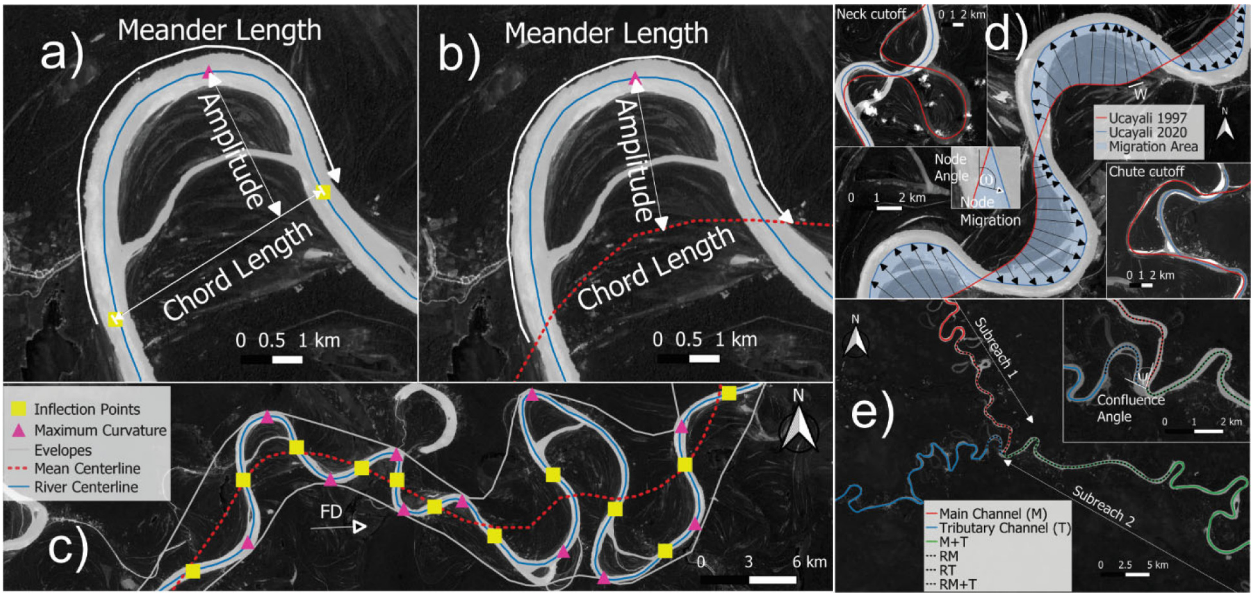


**Fig. 1.** Simplified schemes of different modules and tools. (a,b,c) IPM, MCM methods of meandering morphometrics module, (d) migration module, (e) and confluence module.

splines is implemented. The RC then is discretized at an equal-spacing using *W*. Previous researches have demonstrated that the discretization of the RC at an interval of approximately one *W* remove sufficient noise in the RC [16,25]. While the RC can be extracted by hand-drawing, it can also be extracted in an automated fashion using existing models for meandering channel analysis with satellite images, since the spatial extent of the targeted reach can be large. Such models include channel planform statistic tool [8], RivWidth [26], RivMAP [14], SCREAM [13], PyRIS [15], and RivWidthCloud [27].

M1 offers two tools: the meander geometry tool and wavelet analysis tool. The former analyses the geometric parameters of the RC at each bend detected through classical methodology [28,29]. It calculates RC's sinuosity, meander length (i.e. half of arc-wavelength of the classical definition), chord length, meander amplitude, and meander orientation for each bend detected (Fig. 1a-c). Two methodologies are offered for bend detection: inflection point method (IPM) and mean center method (MCM). IPM defines a *meander bend* as a 'segment of the RC between two consecutive points of zero-curvature' (zero-crossing; Fig. 1a). MCM defines a *meander bend* as a 'segment of the RC between two consecutive intersections between the MC and the RC' (Fig. 1b).

The latter, the wavelet analysis tool, performs the CWT analysis, which allows for the determination of spatial distribution and periodicity of the normalized arc-wavelength [16,19] using the curvature fluctuations signal. This tool then determines the wavelet spectrum and dominant arc-wavelength at user-specified confidence, whose default value is set to 95%.

These two tools offered in the M1 be used in a complementary manner. They combine a discrete analysis, segmenting the study signal (meander geometry), and an integral framework (wavelet analysis).

M2 quantifies the lateral channel migration rate and its spatial pattern. It also detects the cutoff events within two RCs from two different periods of times. It first defines the migration area by intersection points of the two RCs. This step is followed by drawing orthogonally from initial -to- end time RCs, which is defined as the node migration. The migration rate is then calculated by dividing the node migration by the elapsed time between the two RCs (Fig. 1d). Additionally, the module calculates the northward angle ($\omega_i$) of each node migration in degrees. The module also identifies meander cutoff [30]. The cutoffs are identified when there is a decrease in arc-wavelength in the RC of later time compared to that of the earlier time is detected (Fig. 1d). It should be noted that M2 does not distinguish between neck cutoff and chute cutoff.

Post-confluent of meandering channels with different curvature signal, a disturbance is generated along the channel planform [19]. Using the wavelet spectrum, M3 quantifies the disturbance generated by the tributary on the main channel planform geometry, both upstream and downstream of the confluence. Here, the main channel upstream of the confluence is labeled as M, tributary is T, and the main channel downstream of the confluence is MT (Fig. 1e). This module determines the length of influence for the three channels: $R_M$, $R_T$, and $R_{MT}$, respectively, where subscripts denote the three channels M, T, and MT, respectively. First, the wavelet spectrum of the main channel and the tributary at 95% significance is calculated. The module defines by default the length of influence $R_M$, $R_T$, and $R_{M+T}$ as the distance from the confluence point to the first confidence area in the wavelet spectrum, downstream and upstream along the main and tributary channels. In addition, it also calculates the geometrical ratios: the ratio of width ($\beta$), which is the ratio of the tributary channel width ($W_T$) to the main channel width ($W_M$); the arc-wavelength ratio of the tributary ($\lambda_T$) to the main channel ($\lambda_M$); and the confluence angle ($\psi$). A detailed derivation and discussion on these geometric parameters are provided in [19].

## 4. Implementation

MStaT provides an online user manual, which can be found at https://github.com/ldominguezruben/meanderstatisticstoolbox/tree/main/usermanual. A series of tests and examples are also documented and available at https://github.com/ldominguezruben/meanderstatisticstoolbox/tree/main/examples and https://meanderstatistics.blogspot.com/p/tutorials.html. Additionally, the installation steps of the compiled version and external packages can be found at https://meanderstatistics.blogspot.com/p/download.html. The compiled version can execute each module as a standalone. The user can also execute the GUI following the scripts from MATLAB console *'mStat.m'*. Please refer to Supplementary File 1 in Appendix A (MMC S1) or to MStaT website https://

meanderstatistics.blogspot.com, where further information about the technical details can be found. An explanatory video is also provided in Supplementary File 2, Appendix A (Video S1).

## 5. Illustrative examples

Here we show the application of MStaT for the case of the Amazonian Rivers [16,19]. While the use of M1 is shown in the main text of the paper, the demonstrations of M2 and M3 are provided in Supplementary File 1, 2 in Appendix A.

Approximately 300 km of the Huallaga River in 1997 and 2017 were selected for MStaT demonstration. Fig. 2a shows inflection points, maximum curvature, and MC for the Huallaga River. Fig. 2b shows a summary of the meander geometry tool, which illustrates high spatial variation in sinuosity, meander length, and chord length for each *meander bend*. For the demonstration purposes, the results of IPM and MCM are also shown. It should be noted that the definition of *meander bend* is different for the IPM and the MCM, thus, the plots by IPM and those by MCM do not share the same $x$-axis. With the aim of demonstrate the spatial pattern of the results in a comparable manner the data are illustrated in mirrored form.

The results of the wavelet analysis for 1997 and 2017 indicate that the meander curvature signal has not undergone significant changes along the studied reach (Fig. 2c1, where $C^*$ is the curvature normalized by $W$). However, the analysis does detect abrupt changes in arc-wavelength normalized by $W$ ($\lambda^*$) for both years, which are highlighted on the CWT spectra (Fig. 2c2, 2c3). The channel between $0S^*$ and $200S^*$ (where $S^*$ denotes downstream distance normalized by $W$) is characterized by a mixture of short and medium arc-wavelength with the highest being $16\lambda^*$, which appear in approximately at 10–$60S^*$. Downstream reach (i.e. above $200S^*$) is characterized by a longer arc-wavelength with a maximum value of $32\lambda^*$ and an extending substantial downstream distance. This last pattern seems to be more pronounced for the last registry (2017). The global arc-wavelength is found to be $21.05\lambda^*$ for 1997 (black line in Fig. 2c4) and $22.55\lambda^*$ for 2017 (red line in Fig. 2c4), respectively. It means that the global arc-wavelength increased by $1.5\lambda^*$ in 20 years. Finally, CWT analyses allows us to indicate where and how $\lambda^*$ changes along RC.

The complementary reading of outputs achieved through the application of the previous tools allows a novel and improved interpretation of the meandering channels, among which we can mention the appropriate discrimination of spatio-temporal periodicity, and magnitude and global arc-wavelength patterns.

## 6. Impact

MStaT improves the classical morphodynamics characterization of meandering channels by combining a novel wavelet analysis integrated into an easy-to-use standalone GUI with graphical results, which represents a powerful tool for teaching, scientific, engineering, and policy making communities. Understanding the spatio-temporal dynamics of a meandering RC curvature signals, the confluence region instability floodplain (valley) in a comprehensive manner results in a significant improvement to understand the complex nature of meandering river systems. Furthermore, MStaT allows the evaluation of river migration using wavelet analysis to indicate, how and when the highest and lowest migration rates occur, as well as to identify cutoff events. It can also provide a quantitative description of river confluence dynamics, especially for tropical rivers, which are currently poorly understood, while human intervention is significant [31].

MStaT can also be used for river restoration practices. Disturbance due to, for instance, increased runoff by urbanization or the removal of aging dam structures can be quantified, and the mitigation measures can be improved with a better understanding of the meandering dynamics. It should also be noted that the use of MStaT depends on the satellite information available and no additional data acquisition cost is required (e.g. field campaign data).

MStaT is available in a modular package in two formats: a compiled version and the open-source code, which provides access to MStaT to a wide range of potential users. If the user has programming background, he/she may improve and expand the current version. We encourage meandering dynamics researchers to collaborate so as to be able to incorporate their insights into future versions of MStaT.

Meandering patterns represent one of many channel patterns. Future research, therefore, should include extending the framework to incorporate characterization of the multi-channel systems such as braided rivers and anabranching rivers. In studying such systems, parameters to be analyzed should include island geometry, bifurcations, and junction angles.

Finally, MStaT can potentially complement meandering river dynamics models, such as RVR Meander [12], which provides long-term representations of meanders' evolution.

## 7. Conclusions

The principal aim of this research is to provide a user-friendly standalone GUI to the scientific and engineering community. It enables a comprehensive study of the planform geometry of large meandering channels at high spatio-temporal resolution. The software offers a combination of a short and medium-term framework based on the mathematical wavelet methods, which, in addition to the classical characterization, improves the geometry quantification of intricate and large bends such as those present in Amazonian meandering channels. Due to the optimization of MStaT algorithms, it does not require the use of parallelization computational resources, which significantly minimizes computational costs. The MStaT source code is open and designed in such a way that it can be modified and expanded by the user. We believe that the framework presented here takes us one step forward towards a better understanding of the natural fluvial systems as it is based on the scientific meandering morphodynamics frameworks proposed by [16,19].

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.softx.2021.100674.

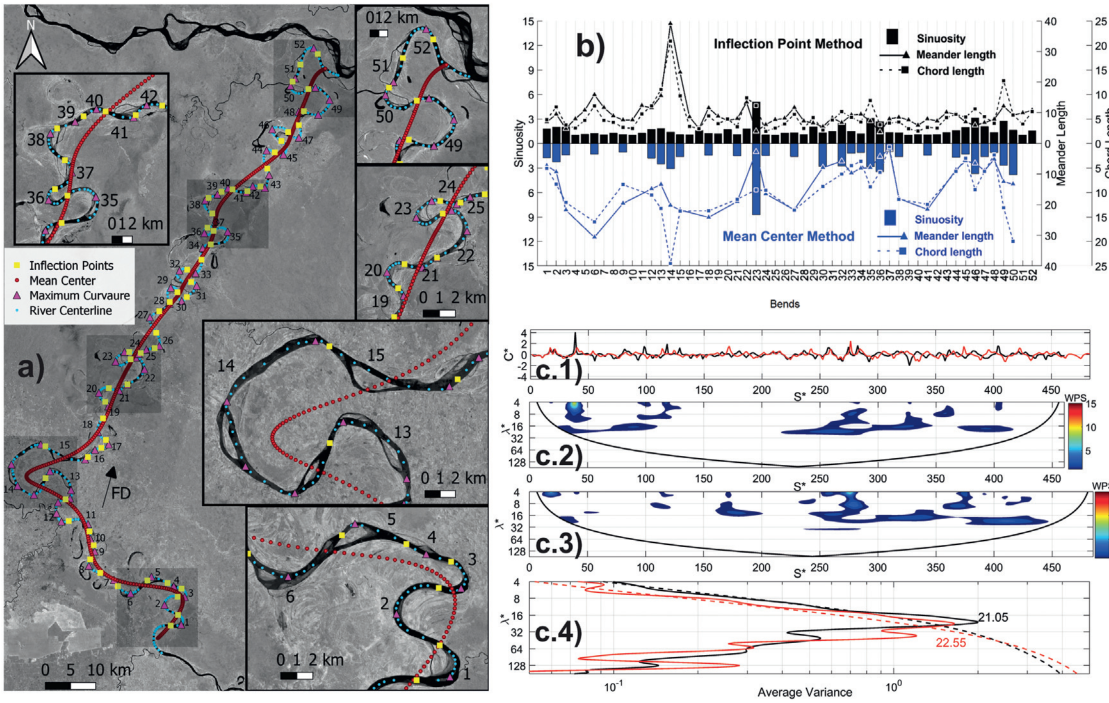


**Fig. 2.** (a) Output of meandering morphometrics module in the Huallaga River (2017). The background is a Sentinel 2 image; (b) Mirror results of IPM and MCM method; (c.1) wavelet analysis of the Huallaga River for the 1997 (black-line) and 2017 (red-line) years the $C^{*}$-$S^{*}$ signal; (c.2) wavelet spectrum of the arc-wavelength hat 95% of confidence (the black line represents the cone of influence) for the 1997 year; (c.3) for the 2017 year and (c.4) the wavelet global spectrum for the normalized curvature of Huallaga River for 1997 (black-line) and 2017 (red-line). The dotted line represents the 95% interval of confidential for the same period time.

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