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SENSITIVITY OF THE FLUVIAL MORPHODYNAMICS TO HYDROMORPHOLOGICAL FACTORS

Application to a Case Study

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To my parents,

I’m like a rock,

Shaped by the water.

I’m smoother now,

But before I was sharped,

Like a sword.

Rafael Santos

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I want to thank to my advisor Rodrigo Maia for showing me the right track in the process of writing this thesis. A special thanks to Bruno Oliveira, my co-advisor, for the promptitude and great advises given along the writing of this thesis.

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To conclude, I finish this chapter by thanking to Mrs. Esmeralda for the good spirit that she carries with her when she walks into our study room, being in fact contagious, and for the promptitude to help everyone.

RESUMO

O objetivo deste estudo é clarificar a relação entre a evolução morfológica de um rio e as variáveis mais importantes para a sua definição, por meios de ambas as análises de sensibilidade independente e conjunta (i.e., tendo em consideração as interdependências entre as variáveis relativamente aos seus efeitos na morfodinâmica), e para descrever quantitativamente (i.e., em forma de gráficos) e quantificar a sensibilidade relativa da morfodinâmica às diferentes variáveis analisadas (visando o caudal, a granulometria e a rugosidade do leito).

O método Simulação Monte Carlo (MSC) foi aplicado usando um modelo numérico hidromorfológico (HEC-RAS) para simular os efeitos que diferentes combinações dos valores dos(as) parâmetros/variáveis produzem na morfologia de um trecho do rio Mondego, com respeito a dados de medições de campo reais.

Os resultados mostram um aumento de importância da rugosidade do leito à granulometria e caudal em termos de variações absolutas gerais do nível do leito do rio (impacto total) (≈ 1%, 46% 53%, respetivamente). Adicionalmente, relativamente ao impacto total das variáveis na morfodinâmica, observou-se que a rugosidade do leito produziu efeitos lineares, enquanto que o caudal e a granulometria produziram efeitos não lineares (no entanto monotónicos) na magnitude da morfodinâmica. Comparativamente, a rugosidade do leito do rio foi observada ser de menor importância para a definição da morfodinâmica fluvial.

PALAVRAS-CHAVE: Morfologia de Rios, Simulação Monte Carlo, Modelo 1D, HEC-RAS, Análise de Sensibilidade

ABSTRACT

This study's objective is to clarify the nature of the relationship between a river morphodynamical evolution and the variables most important to its definition, by way of both independent and joint sensitivity analysis (i.e., taking into consideration the interdependencies between the variables regarding their effect on morphodynamics), and to describe both qualitatively (i.e., by way of graphics) and quantitatively the relative sensitivity of morphodynamics to the different variables analysed (viz., flow, granulometry and bed roughness).

The Monte Carlo Simulation (MCS) method was applied by using a hydro-morphodynamic numerical model (HEC-RAS) to simulate the effects that different combinations of parameters/variables' values produce in the morphology of a reach of the of a Mondego river, regarding real field data measurements.

The results show an increasing importance from bed roughness to granulometry and flow in terms of the absolute overall bed level change (total impact) (≈ 1%, 46% and 53%, respectively). Additionally, regarding the total impact of the variables in morphodynamics, bed roughness was observed to produce linear effects, whilst flow and granulometry produced non-linear (albeit monotonic) effects in the magnitude of morphodynamics. Bed roughness was observed to be of comparatively smaller importance for the definition of fluvial morphodynamics.

KEYWORDS: River Morphology, Monte Carlo Simulation, 1D Model, HEC-RAS, Sensitivity Analysis

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SYMBOLS AND ACRONYMS

Q – Flow (m^3/s)

D – Diameter of the sediment

D_{50} – Median diameter of a particle size distribution

n – Bed roughness [$s/(m^{1/3})$]

S_{Ti} – Sobol Indice (Total Effect Index)

MCS – Monte Carlo Simulation

FORM – First Order Reliability Method

AHM – Aproveitamento Hidráulico do Mondego

HEC-RAS – Hydrologic Engineering Center River Analysis System

h_n – Normal depth

1
INTRODUCTION

1.1. OBJECTIVES AND GENERAL FRAMEWORK

The morphological behaviour of a river (i.e., the evolution of erosion and sedimentation processes along the channel's bed) is determined by a multitude of effects. These effects are associated with the different parameters/variables which drive morphological change, each of which has, in turn, its own degree of relevance for the definition of morphodynamics. Sediment transport is a very complex subject, due to the number of variables and their inherent effects to be considered. Thereby, numerical models were created in this work field, being them a tool to study the effects of certain variables which drive morphological changes on a river bed. Several studies based in uncertainty are used as an attempt to represent the uncertainty related to the variables and their inherent effect on morphodynamics by representing their independent and joint interaction with the river bed. Statistics are often used in such cases to approximate hypothetical scenarios to reality.

The present thesis has the aim to:

1. clarify the nature of the relationship between a river morphodynamical evolution and the variables most important to its definition, by way of both independent and joint sensitivity analysis (i.e., taking into consideration the interdependencies between the variables regarding their effect on morphodynamics);
2. describe qualitatively (i.e., by way of graphics) and quantitatively the relative sensitivity of morphodynamics to the different variables analysed.

This study was performed having a stretch of the Mondego river as a case study, of which real field data was used (viz. flow series, granulometric profiles and geometry of the stretch).

To perform this study the method applied made use of the real field data, and it required a hydrodynamical and morphodynamical numerical model such as HEC-RAS (Brunner 2016) to execute a stochastic procedure. A stochastic procedure involves multiple combinations of different variables (regarding their inherent set of values), and it is needed on an attempt to better represent real life events. HEC-RAS is therefore used for the whole simulation process. This numerical model was used to perform a river's stretch behaviour, regarding the bed level change, under various variables' combinations. Thereby, obtaining different the outcomes of the bed level change to be analysed with respect to the variables' influence on morphodynamics. This analysis was divided in independent and joint sensitivity analysis. The first refers to the analysis of each variable, regarding bed level change, independently, and the latter refers to the analysis of the interdependencies between the variables and their individual overall impact, also regarding bed level change.

The variables considered in the analysis of the morphodynamics' sensitivities are, flow (Q), granulometry (D) and roughness (n). These variables were chosen because they have been shown, in multiple studies (such as, (Van Vuren 2005; Oliveira and Maia 2018; Visconti, Camporeale, and Ridolfi 2010)) as having a strong influence in morphodynamics and because they directly affect real life morphodynamics and not just the numerical models themselves (unlike other variables which are just underlying factors of the simulation of morphodynamical processes, often relating to the incipient motion or bed load transport (e.g., critical shields shear stress)). When studying fluvial morphodynamics the effects of some variables are often disregarded in the calculations, since they produce comparatively smaller effects and the complexity of introducing each one on the calculations is very high because the effect produced by each variable and its corresponding value are difficult to measure.

Different studies have put greater emphasis on different variables (Mouradi et al. 2016; Oliveira and Maia 2018; Van Vuren 2005), simulating the variable's uncertainty and analysing the sensitivity of morphodynamics from the perspective of its individual effect on morphodynamics. Other examples of these variables include the sediment's critical shear stress, and particle entrainment and deposition processes (particularly in the case of small scale stochastic processes).

Risk analysis generally involves experimenting with multiple values of each variable, providing a more representative description, in extension and magnitude, of the variables under analysis. In the present study, the focus is mostly on the understanding of morphodynamics, which suffer from a large amount of uncertainty, being it related to the variables or to its definition from a scientific point of view. The present study attempts to clarify the relationship between the different variables and a river's overall bed level change, as well as analysing the importance of each variable to the morphodynamical evolution, thereby assisting future studies in engineering research and investigation in the comprehension and representation of the uncertainty effects on morphodynamics.

Independent sensitivity analysis intends to better represent the dependency between each variable and a set of statistics representing the different aspects of morphodynamics. This analysis was based on the variables' partial mean values of the river morphological changes throughout the simulations. Each variable's effect in the range of morphological changes was thereby isolated in order to allow the identification of its hierarchical importance (in comparison with the other variables) and providing an understanding of the linearity/non-linearity of its relationship with morphodynamics.

Studies on independent and joint sensitivity analysis of morphodynamics aim to represent the influence of the variables in morphodynamics, namely, by using a numerical model to perform multiple simulations for different combinations of variables and analysing the corresponding range of possible morphologies has been, in most cases, the adopted technique/concept. The joint sensitivity analysis applied in this study requires the application of a numerical hydro-morphodynamic model, which can be a time-consuming process but provides a good representation of the morphodynamics' behaviour. This approach provides a representation of the sensitivity of morphodynamics, to some extent, the interdependency of the variables and the non-linearity of morphodynamics' sensitivities.

The method Monte Carlo Simulation (MCS), which consists in a stochastic procedure and in a posterior statistical approach, was carried out using the following software:

1. HEC-RAS for the stochastic procedure on river modelling considering multiple combinations of the variables' values;
2. Excel used for the independent sensitivity analysis;
3. R for the statistical approach, regarding the joint sensitivity analysis.

These simulations are intended to provide an approximation to the average bed change that would effectively occur in real life conditions. Additionally, the assessment of the simulations' results is meant to provide a better understanding of the corresponding relationship between morphodynamics and the variables, as well as, a quantitative comparison between each variable to identify their hierarchic order of overall relative importance to the river's bed change.

In order to quantify morphodynamical change, 4 morphodynamical aspects were considered in the independent sensitivity analysis, namely, erosion, sedimentation, balance and total impact. Erosion represents the negative values of the river's bed level change, sedimentation represents the areas where there was an increase in bed level, balance was represented by the mean elevation values (i.e., considering both erosion and deposition), and the total impact represents the absolute mean elevation values (i.e., considering the absolute values of the bed level's variations relative to the initial bed level). Joint sensitivity analysis was performed based on variance-based estimates of the variables importance, namely on the variance based global sensitivity analysis, of which several statistics were analysed.

1.2. Structure of the Thesis

The present work is organized in six chapters, in the following order:

The first chapter corresponds to the introduction of this thesis and is intended to provide a context for the present study (viz., morphodynamical behaviour of a river bed) and explain the adopted approach regarding the morphodynamics' sensitivities (i.e., considering the relationship between the selected variables and the morphological changes of a river bed).

The second chapter, designated as the state of the art, lays out some important information on the stochastic nature of morphodynamics, as well as some insights on the studies performed by other researchers and investigators in the present field of morphodynamics, additionally laying the groundwork to justify some of choices made for the present work.

The third chapter is a presentation of the case study, as well as additional information relative to it, such as its location, climate, management entity and the data used in the software to carry out the simulations.

The fourth chapter presents the methodology adopted for the purpose of this study, namely, the software used, the considerations made regarding some data and the calculation procedure to analyse the respective simulations' results.

The fifth chapter (titled, numerical modelling – results' analyses), presents an analysis of the simulations' results, namely for both the independent and joint sensitivity analysis, as well as a posterior discussion of the results' analyses in an overall perspective, establishing a comparison between the results obtained in this study and the results obtained in other related studies.

The sixth chapter, i.e., the conclusions, summarizes the conclusions and reflections in this study and the future developments to be made in the subject of this thesis.

2
STATE OF THE ART

The stochastic modelling of fluvial morphodynamics and the sensitivity analysis of the related input variables is a relatively new area in science and engineering, primarily due to the computational costs of said modelling. Nonetheless, this chapter presents some of the most important concepts regarding the modelling of fluvial morphodynamics and its analysis (based on a literature review of previous studies on these subjects). This chapter presents information regarding: (1) the importance of the study of the statistical aspects involved in river morphology (2) the stochastic modelling approach (namely, its importance, some of the most commonly used methods and uncertainty as part of the models' input data, particularly in the context of selecting the variables most relevant to fluvial morphodynamics) and (3) the morphological response statistics (regarding the results obtained for different variables' model input sets).

2.1. UNCERTAINTY IN RIVER MORPHOLOGY

A river system is a strongly dynamic system, whose forecasting, whilst of great interest to a variety of fields of study, suffers from a high uncertainty and thereby presents a challenge to both scientists and engineers. Additionally, the definition of this uncertainty requires a careful selection of the different uncertainty sources, as attempting a complete representation of uncertainty is not reasonable given the high difficulty to define the correct effects produced by these uncertainty sources.

The uncertainty involved in the forecasting of morphodynamical behaviour can generate added risk to humanity's safety, since the erodibility of the river bed is one of the elements that can cause damage to hydraulic structures (e.g., dams, bridges, underwater tunnels). Natural morphological changes are directly related to several parameters, being flow considered the most relevant parameter, since it is responsible for the sediment conveyance processes, by the increase of the flooded area and water level. Therefore, the forecast of river morphological changes is adjacent to other uncertain analysis research areas (viz., meteorology, hydrology, ecology, public health, climatology and hydraulic engineering) (Bruk 1995; Chang 2008; Van Vuren 2005). One example of a city that from time to time has problems with flood events, regarding the Mondego river, is the city of Coimbra. The last major flood events are the ones of 1962, 1969 and 1979, and the return period, in the last 2 centuries, changed from 50 to 20 years (S. Rocha and Freitas 1998). Thereby, it's evident the necessity to control floods, in such cases, and the use of stochastic models may permit the pro-active forecast/prevention of this type of events.

The combination of this multitude of aspects, particularly in a statistical environment requires an extensive study of these same aspects. Accordingly, the analysis of the morphological behaviour of a river bed (from a statistical point of view) must be performed using a stochastic model approach.

2.2. STOCHASTIC MODEL APPROACH

A deterministic and stochastic approach is directly attached, by definition, to dynamic state

The static analysis of river morphology generally consists of defining the river and the variables involved as constant or very slowly varying (such as an equilibrium state forms under constant flow conditions). However, the variation of the different forcing factors of fluvial morphodynamics implicates the analysis of a river system to change from a static to a dynamic state. A deterministic and stochastic approach is directly attached, by definition, to dynamic state. Variation underlies dynamics, since the latter is represented by the capacity of a variable to change while mutually interacting. Thereby, a dynamic approach presents the evolution of a river system over time, additionally, flow is in constant variation.

A deterministic approach to numerical modelling can be simply understood as the application of numerical models were the definition of the input variables are deemed as correct and/or sufficiently well determined. A stochastic approach is the combination of a deterministic dynamic approach with the different aspects of uncertainty involved. The word stochastic generally refers to variables which are random in nature but also dependent over time, be it on themselves, on other variables or on time itself (Bass 2011). The representation of uncertainty can be a useful component in the analysis of a river system since (1) a deterministic model is sometimes unable to represent some of the complex physical morphodynamic processes or phenomena (particularly those with a statistical nature) (Nabi, De Vriend, and Mosselman 2012) and (2) the ability to accurately quantify model inputs and parameters can be, to some extent, improved upon.

2.2.1. IMPORTANCE OF STOCHASTIC MODELLING

Stochastic modelling comes as an attempt to clarify fluvial morphodynamical behaviour whilst taking into consideration the dynamic and random nature of river systems, exhibiting uncertainty in space and time. It allows to define a certainty degree of the obtained results, to execute analyses of risk and cost-benefit investment, and to understand the natural variability of rivers' behaviour. Given the uncertainty inherent to the lack of accuracy present on data measurements, the model's predictions of the future (and present) behaviour of a river are also uncertain. Whilst this uncertainty is itself unavoidable, the overall importance of the uncertainty regarding the variables in analysis can be represented by several stochastic methods (Van Vuren 2005) (a few of which are mentioned in section 2.2.3.). These stochastic methods are mathematical tools that help in dealing with uncertainty in a responsible manner. Engineers have been using a variety of these tools in the determination of hydrodynamic and morphological response to engineering enterprises. Additionally, engineers, investigators and researchers have been trying to improve on the deterministic approaches by taking in count multiple possible situations that may occur in a river. Therefore, the development of numerical models has been improving, and a stochastic model approach is now possible for both the simple one-dimensional (1D) models and for the more sophisticated 2D and 3D models (Van Vuren et al., 2016).

2.2.2. STOCHASTIC METHODS

Stochastic methods are characterised by the use of mathematical models as an approach to represent the sensitivities of the models' outputs (in this case the morphodynamical sensitivities), as well as, the corresponding uncertainty associated with the data measurements or the input variables of the computational numerical models. These models are often characterised by some or all of the following properties (as described by Van Vuren (Van Vuren 2005)):

- many input and output variables;
- model is time-consuming to run on a computer;
- alterations to the model are difficult and time-consuming;
- it is difficult to reduce the model to a single system of equations;
- discontinuities exist in the behaviour of the model;
- correlation exist between the model input variables;
- the associated marginal probability distributions of the model input variables are often non-normal;
- model predictions are non-linear multivariate time-dependent functions of the input variables;
- the relative importance of the individual input variables is a function of time.

A stochastic method has the objective of quantifying uncertainties (i.e., by means of statistical characteristics) in the model output. Additionally, it can be used for the estimation of the relative contribution of several sources of uncertainty in the model input to the overall uncertainty in the model output.

Several stochastic methods are considered suitable for the study of the stochastic nature of a river morphological behaviour.

The model output is taken as Y and it's assumed to be a function of p stochastic variables, taken as X_i.

$$Y = g\left(X_1, X_2, ..., X_p\right) = g\left(\vec{X}\right) | g : \Re^p \rightarrow \Re^1 \tag{2.1}$$

Thereby, the cumulative probability distribution function of Y is defined as a function of the probability density functions of the stochastic variables, being:

$$F(Y) = \int_{-\infty}^{X_p} \int_{-\infty}^{X_p} ... \int_{-\infty}^{X_1} f_{X_1, X_2, ..., X_p}(X_1, X_2, ..., X_p) dx_1, dx_2, ..., dx_p \tag{2.2}$$

The most commonly used stochastic methods are Numerical Integration, Monte Carlo Simulation (MCS), First Order Reliability Method (FORM), Response Surface Replacement Method and Stochastic Differential Equations. Some of these stochastic methods cannot always be executed analytically, therefore numerical methods are used to estimate the solution.

In Numerical Integration, discretisation is used to approximate (Eq. 2.2) analytically. MCS approximates the output statistics (shown on Eq. 2.2) by running a deterministic model of output Y (as an approximation to Eq. 2.1) repeatedly. A different set of model inputs (statistically equivalent) is applied on each run. FORM linearizes the function of the model output (Eq. 2.1) and determines the statistics inherent to those same outputs. Response Surface Replacement replaces the output function (Eq. 2.1) by developing a meta-model. The developed meta-model derives all inferences, regarding the uncertainty and sensitivity analyses for the model output function (Eq. 2.1). Stochastic Differential Equations considers both input variables X_i and the output function (Eq. 2.1) (describing the physical system behaviour) of a stochastic nature.

As an example, this thesis evaluates the sensitivities of morphodynamics, namely regarding the overall importance of the variables and the interdependencies between them by way of the Monte Carlo Simulation (MCS) method, applied using the computational numerical model HEC-RAS (Brunner 2016). The MCS method consists of running a numerical computational model multiple times, each time with a different set of input data (for all or some of the input variables) to obtain results from a variety of combinations. The MCS method allows for the analysis of the model's results from a statistical point of view (for example by using a crude sampling of the input variables), in terms of its expected values, variances, percentiles and confidence intervals inherent to the sensitivity analysis (both in terms of their respective variables' uncertainties and interdependencies) (Oliveira and Maia 2018; Van Vuren 2005). Additionally, the quantification of the overall importance of the variables in analysis contributes to the prioritization of the model inputs (JJP, HRA, and H Van 2004; Mouradi et al. 2016; Warmink and Booij 2015).

Stochastic methods study the nature of fluvial morphodynamics considering its inherent uncertainty. Their applicability is dependent on how well these methods deal with the strong non-linearity and complexity of river morphology and on the source of their input data, since some of the relevant variables are often studied according to field data and others according to hypothetical data, or defined variability range for each variable. In addition, stochastic models are recommendable, since in the present-day engineering practice, deterministic fluvial hydro-morphological models are commonly used tools that facilitate the stochastic procedure (Beckers, Noack, and Wieprecht 2016; Borsányi et al. 2014; Van Vuren 2005).

2.2.3. Uncertainty as a Condition for the Models' Input Data and Variable Selection

The selection of the variables most relevant to morphodynamics is an important factor in this type of studies, given the inherent uncertainty associated with multiple variables which affect fluvial morphodynamics. Thereby, credibility is of a great importance to avoid a large spreading of uncertainty which can translate into virtually useless results. When selecting a variable, the uncertainty related to the different choices should be mentioned as insight for the understanding of possible unexpected results. Additionally, if the level of uncertainty is too high, only the parts of the analysis that can still be trusted should be considered and communicated (Borsányi et al. 2014).

Many studies use stochastic techniques in order to estimate the relative contribution of each model input, thereby enabling to discriminate between the more important and the less important uncertainty sources/input variables. It is clear that in fluvial morphodynamics there exists a large number of uncertainty factors to be considered, however it is known that some of these factors can be considered as (comparatively) negligible in terms of their respective impact on morphological changes (Van Vuren 2005). Accordingly, these factors can reasonably be estimate to an appropriate value/magnitude. Finally, many of these techniques are dependent on regression methods in which linearity (in terms of certain aspects of the variables behaviour) is assumed and it is important to evaluate the appropriateness of such assumptions in these analysis techniques. (J. Beven et al. 2006; Pappenberger et al. 2005).

Several factors of the fluvial uncertainty are strongly interlinked and/or independent. Uncertainties present in the model simulations are generally directly connected to uncertainties in the model structure, the model parameters and in the forcing terms. The process of model calibration aims to specifically minimise simulation errors by providing a better parameter estimate. Albeit the input, output and model structure are dependent on systematic and random errors, a proper model calibration may result in parameters choices that compensate, to some extent, the uncertainties or give more precision to the calibration process (B. Butts et al. 2004). Determining the source of most errors can often be difficult to accomplish, a factor against which the calibration can provide some measure of protection.

2.3. Morphodynamic Sensitivity Analysis

Multiple studies have been carried out regarding the statistical understanding of the behaviour of morphodynamics, namely by considering a variety of variables, simulating the variables' uncertainty and analysing the sensitivity of morphodynamics, with regards to individual statistics, such as the critical Shields parameter, the exponent of the bed shear stress in the transport formula, stochastic particle entrainment, settling, and erosion. Other studies focus on the joint sensitivity analysis of morphodynamics, and evaluate the range of the morphological changes produced by the respective variables for a variety of combinations of the input variables values (Oliveira and Maia 2018).

As an example, Oliveira and Maia (Oliveira and Maia 2018) conducted a study using a numerical hydro and morphodynamic model to approximate and represent the relationship between morphodynamics (i.e., the evolution of the channel's bed shape over time) and the variables which are most important to its definition, both in terms of overall magnitude and distribution/pattern over the channel bed. The objective of the study was to obtain a complete description of the characteristics and intensity of the relationship between morphodynamics and the variables, along with a quantitative description of the morphodynamics' relative sensitivities, for which the variables considered were the flow, granulometry and bed roughness.

Saskia Van Vuren (Van Vuren 2005) analysed other uncertainty sources, and its importance to morphology was obtained with a global sensitivity analysis. In this case, the morphological response is most sensitive to parameters of the sediment transport formula, (viz., the exponent of the bed shear stress and the critical Shields parameter).

One of the conclusions taken from (Oliveira and Maia 2018) is that the hierarchical order (regarding the overall relative importance to morphological changes) is flow, bed roughness and granulometry, from the highest to the lowest, respectively. This variables' relative importance was quantified by taking several different statistics into count. The relative importance percentages determined were of 55%, 30% and 15%.

The interpretation of the results of MCS and the estimation of the relative contribution of the different variables cannot be performed directly from the data. The combination of the space and time dependent signature and the time-lag effect (i.e., hysteresis) with the non-linear behaviour of morphodynamic systems eventually results in complex interactions of the different uncertainty sources, increasing the overall uncertainty. In the study by Van Vuren (Van Vuren 2005), it was made clear that, no clear statement on the relative importance of uncertainty sources to the overall uncertainty in the morphological response can be made, due to river systems having a verifiably non-linear behaviour. Generally speaking, bed roughness, the critical Shields parameter and the exponent of the bed shear stress in the transport formula, were the parameters with the most importance to morphological changes. The flow's importance to morphological changes presents a seasonal variation, being more significant at locations with non-uniformities in geometry, and the importance of the grain size was (comparatively) of smaller importance (Van Vuren 2005).

In comparison with the work developed by Oliveira and Maia (Oliveira and Maia 2018), the paper produced by Van Vuren (Van Vuren 2005) presented more variables in analysis, although the importance given to the variables was only analysed qualitatively and the importance of morphologically relevant variables was obfuscated by the importance of variables relevant solely for the numerical models.

3
CASE STUDY

In the present chapter, the case study used in this thesis is completely defined, thereby providing a context for the study of morphodynamics and presenting all of the relevant information. The main elements of this case study are presented, namely regarding its geometry, its boundary conditions, the data sets available regarding the variables under analysis and other general considerations. The case study upon which this thesis was created corresponds to a stretch of the Mondego river. The Mondego river was selected for analysis due to the considerable amount of data available. This available data consists of (a) the geometry of a stretch of the river, (b) different flow series (each corresponding to a 3-month period of flow data measurements, equivalent to the wetter periods of each of the 5 years of flow data on record, approximately situated between January and March) and (c) granulometric profiles taken from different locations along the river. In the present chapter this data is presented, and it has the purpose of a more realistic results' achievement. The results obtained in this thesis (namely based on this case study) are intended to provide a better description of the behaviour of morphodynamics and to provide more solid foundations for future studies on the uncertainty of fluvial morphodynamics.

The available data was taken from a related study. The flow data corresponds to flow series discharged from the two dams situated upstream from the stretch under analysis and they were corrected by the hysteresis of the river's channel in the interval comprehended between the dams and the stretch's starting point.

3.1. CHARACTERISTICS OF THE MONDEGO RIVER

The Mondego river is a portuguese river which begins in *Serra da Estrela* mountain range at 1525 metres above the sea level and has a length of approximately 258 kilometres. It flows through the districts of Guarda, Viseu and Coimbra, and its mouth is situated in the Atlantic Ocean next to the city of Figueira da Foz.

The area of the Mondego river's basin is of approximately 6645km^2, it is characterized by a Mediterranean climate with a strong inter-annual flow variation and accentuated seaonal events of flooding and drying over an annual cycle. The basin has a mean annual precipitation around 1233 mm and a mean annual flow of 108.3 m^3/s.

The Mondego river is divided between the *Alto Mondego* and *Baixo Mondego*, which *Baixo Mondego* consists in the last 40km until the mouth. The sediments present in each one are different, being the sediments present in *Alto Mondego* of a larger size, mostly composed by metamorphic rocks, shale and granite and in *Baixo Mondego* is mostly a vast alluvial plain which goes downstream until the river's mouth.

The management entity of Mondego river, namely, AHM (*Aproveitamento Hidráulico do Mondego*) which is responsible for managing the water resource exploitation in the river. The basin of the Mondego river is considered as one of the portuguese basins with the most intense usage of its hydric resources, especially for the components of hydroelectric generation and agriculture. The Aguieira, Raiva and Fronhas dams particularly stand out with a joint power potential of 110MW and a mean annual productivity of 360 GWh, whilst also providing water for public usage of some municipalities of the *Baixo Mondego* area.

The Mondego river, receives water from several tributaries. Upstream from the referred case study's reach, the Alva river enters the Mondego river, thereby contributing to its flow. The Fronhas dam (situated in the Alva river) performs multiple discharges throughout the year. These discharges intersect with the discharges of the Raiva dam (located in the Mondego river itself) and with the natural flow runoff along the channel coming from the surrounding basin, downstream from both dams.

3.2. LOCATION

The stretch of the Mondego river which was analysed in this study is located close to Coimbra city. The corresponding reach's upstream boundary is situated near Palheiros (at the Palheiros levee) and the downstream end is at the Portela do Mondego bridge, for a total length of 3327 metres.

Figure 1 presents an aerial view of the reach under analysis, as well as locations of the upstream and downstream boundaries. It also shows the approximate location of the river stretch in Portugal, being represented by a red rectangle and the Mondego river by a blue line.

Figure 1 - Plant view of the stretch in analysis; upstream and downstream boundaries.

3.3. GEOMETRY DATA

The geometry data available for this study consisted of a set of 200 cross-sections, the main overall characteristics of which are presented in Table 1. Figure 2 provides a graphical representation of the spacing and relative locations of each the cross-sections.

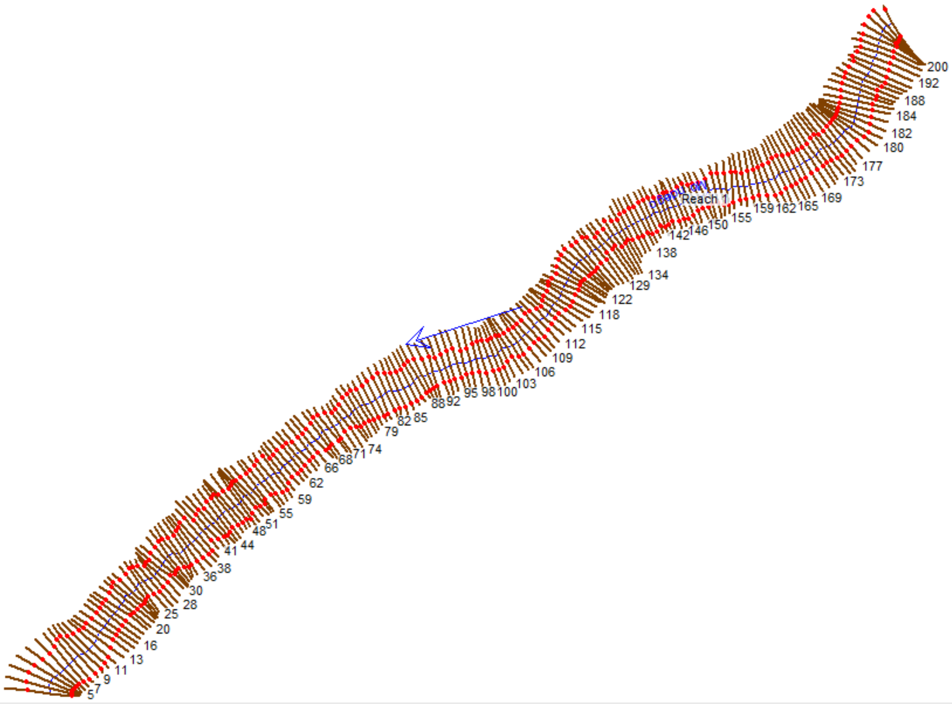

Figure 2 – Case Study reach of the Mondego river, represented by its corresponding 200 cross-sections in HEC-RAS; The blue arrow represents the stream direction, from upstream to downstream

Table 1 – Case Study's channel's characteristics

	Length Between Cross-sections (m)	Top Cross-Sections' Width (m)	Elevation (m)
Minimum	14.5	113.3	17.0
Mean	16.6	160.7	15.7
Maximum	19.6	214.1	19.4

As seen in Table 1, the distance between cross-sections is relatively small, going up to approximately 20 metres, thereby providing a reasonable degree of precision for the study of the respective channel's morphodynamics and the corresponding bathymetry/topography. The top cross-section width corresponds to the distance (measured along the horizontal direction) between the top left and top right points of the cross-section.

The channel geometry used in the simulations (further specified in Section 4) consists of 200 cross-sections. The criteria for defining the limits of the main channel corresponds to a steady discharge magnitude at the upstream boundary of 140 m3/s (estimated to be one of the most common discharge levels based on the observed data and the discharge capacity of the Raiva/Aguieira and Fronhas Dams). From this simulation, the mean water depth was estimated to be of approximately 3.3 meters.

3.4. Variables' Data

In this section the available data regarding the flow and granulometry variables is presented.

The available data consists of 5 flow series and 6 granulometric profiles. Each of the flow series consists of a hydrological year's highest flow 3-month period (most often located around the months of January to March), for a total of 5 years of measurements corresponding to the years of 2010 to 2014. The granulometric profiles were taken from different stretches of Mondego.

3.4.1. Granulometry

The granulometric profiles considered in the present study are presented in Table 2, 3, 4, 5, 6 and 7. Each granulometric profile was measured in a different location of the Mondego river. The corresponding location, measured in kilometres from the river's estuary, is specified in the tables. The acronyms (P1, P2, P3, P4, P5 and P6) were used to identify the profiles in a hierarchical order, namely, from the lowest to the highest corresponding D_{50} value, respectively. The D_{50} value is known as the median diameter or the medium value of the particle size distribution, representing the particle diameter at 50% in the cumulative distribution.

Table 2 - Granulometric Profile 1

Profile P1 (Km 20.410)				
Sieves		Sample		
#	(mm)	Mass Retained (gr)	% Retained	% Passed
S.3"	76.10	0.0	0.00	100.00
S.2"	50.80	0.0	0.00	100.00
S. 1 1/2"	38.10	0.0	0.00	100.00
S.1"	25.40	0.0	0.00	100.00
S.3/4"	19.00	0.0	0.00	100.00
S. 1/2"	12.70	0.0	0.00	100.00
S. 3/8"	9.51	2.8	0.15	99.85
S. 3	6.30	24.3	1.33	98.52
S.4	4.76	76.1	4.17	94.34
S.8	2.36	364.9	20.01	74.33
S.16	1.25	685.0	37.57	36.76
S.30	0.63	465.9	25.55	11.21
S.50	0.315	163.6	8.97	2.24
S.100	0.16	38.4	2.11	0.12
S.200	0.074	1.3	0.07	0.05
Bottom		1.0	0.05	0.00
Total		1823.3	100	

Table 3 - Granulometric Profile 2

Profile P2 (Km 49.456)				
Sieves		Sample		
#	(mm)	Mass Retained (gr)	% Retained	% Passed
S.3"	76.10	0.0	0.00	100.00
S.2"	50.80	0.0	0.00	100.00
S. 1 1/2"	38.10	0.0	0.00	100.00
S.1"	25.40	0.0	0.00	100.00
S.3/4"	19.00	0.0	0.00	100.00
S. 1/2"	12.70	5.3	0.21	99.79
S. 3/8"	9.51	21.5	0.86	98.93
S. 3	6.30	148.1	5.92	93.01
S.4	4.76	423.0	16.92	76.09
S.8	2.36	774.2	30.97	45.12
S.16	1.25	654.7	26.19	18.93
S.30	0.63	383.7	15.35	3.58
S.50	0.315	74.8	2.99	0.59
S.100	0.16	2.3	0.09	0.50
S.200	0.074	0.2	0.01	0.49
Bottom		12.2	0.49	0.00
Total		2500.0	100	

Table 4 - Granulometric Profile 3

Profile P3 (Km 34.946)				
Sieves		Sample		
#	(mm)	Mass Retained (gr)	% Retained	% Passed
S.3"	76.10	0.0	0.00	100.00
S.2"	50.80	0.0	0.00	100.00
S. 1 1/2"	38.10	0.0	0.00	100.00
S.1"	25.40	129.7	4.32	95.68
S.3/4"	19.00	128.4	4.28	91.40
S. 1/2"	12.70	393.6	13.12	78.28
S. 3/8"	9.51	162.3	5.41	72.87
S. 3	6.30	530.1	17.67	55.20
S.4	4.76	324.5	10.82	44.38
S.8	2.36	360.7	12.02	32.36
S.16	1.25	465.9	15.53	16.83
S.30	0.63	333.0	11.10	5.73
S.50	0.315	95.0	3.17	2.56
S.100	0.16	31.8	1.06	1.50
S.200	0.074	2.2	0.07	1.43
Bottom		42.8	1.43	0.00
Total		3000.0	100	

Table 5 - Granulometric Profile 4

Profile P4 (Km 64.525)				
Sieves		Sample		
#	(mm)	Mass Retained (gr)	% Retained	% Passed
S.3"	76.10	0.0	0.00	100.00
S.2"	50.80	240.3	5.59	94.41
S. 1 1/2"	38.10	529.0	12.31	82.10
S.1"	25.40	916.2	21.31	60.79
S.3/4"	19.00	606.5	14.11	46.68
S. 1/2"	12.70	519.8	12.09	34.59
S. 3/8"	9.51	99.5	2.31	32.28
S. 3	6.30	287.2	6.68	25.60
S.4	4.76	159.7	3.72	21.88
S.8	2.36	188.0	4.37	17.51
S.16	1.25	100.4	2.34	15.17
S.30	0.63	69.0	1.61	13.56
S.50	0.315	116.1	2.70	10.86
S.100	0.16	114.2	2.66	8.20
S.200	0.074	31.5	0.73	7.47
Bottom		321.0	7.47	0.00
Total		4298.4	100	

Table 6 - Granulometric Profile 5

Profile P5 (Km 43.322)				
Sieves		Sample		
#	(mm)	Mass Retained (gr)	% Retained	% Passed
S.3"	76.10	0.0	0.00	100.00
S.2"	50.80	194.9	4.14	95.86
S. 1 1/2"	38.10	994.3	21.12	74.74
S.1"	25.40	1288.2	27.36	47.38
S.3/4"	19.00	321.2	6.82	40.56
S. 1/2"	12.70	463.9	9.85	30.71
S. 3/8"	9.51	101.4	2.15	28.56
S. 3	6.30	266.9	5.67	22.89
S.4	4.76	169.4	3.60	19.29
S.8	2.36	305.1	6.48	12.81
S.16	1.25	337.8	7.18	5.63
S.30	0.63	198.6	4.22	1.40
S.50	0.315	33.8	0.72	0.68
S.100	0.16	13.7	0.29	0.39
S.200	0.074	1.0	0.02	0.37
Bottom		17.4	0.37	0.00
Total		4707.6	100	

Table 7 - Granulometric Profile 6

Profile P6 (Km 55.726)				
Sieves		Sample		
#	(mm)	Mass Retained (gr)	% Retained	% Passed
S.3"	76.10	0.0	0.00	100.00
S.2"	50.80	874.4	22.46	77.54
S. 1 1/2"	38.10	828.0	21.26	56.28
S.1"	25.40	367.6	9.44	46.84
S.3/4"	19.00	199.7	5.13	41.71
S. 1/2"	12.70	293.4	7.53	34.18
S. 3/8"	9.51	73.3	1.88	32.30
S. 3	6.30	218.4	5.61	26.69
S.4	4.76	212.9	5.47	21.22
S.8	2.36	319.7	8.21	13.01
S.16	1.25	259.7	6.65	6.36
S.30	0.63	206.6	5.31	1.05
S.50	0.315	23.3	0.60	0.45
S.100	0.16	4.4	0.11	0.34
S.200	0.074	0.7	0.02	0.32
Bottom		12.5	0.32	0.00
Total		3894.6	100	

The granulometric profiles present significant differences between them. Looking at the percentage of material passed in the sieves, it is clear that some granulometric profiles lack larger diameter sediments and others lack of small sized sediments. The most frequent diameter sizes are situated between 4.76 mm and 0.63 mm.

For input data purposes the granulometric data had to be rearranged to meet some requirements of the simulation software adopted. These requirements implied the change of some sieves’ openings, presented in Table 8.

Table 8 – Sieves used on measurements and software sieves

Sieves	
Measurements (mm)	Software (mm)
76.10	128
50.80	64
38.10	
25.40	32
19.00	
12.70	16
9.51	
6.30	8
4.76	
2.36	4
1.25	2
0.63	1
0.315	0.5
0.16	0.25
0.074	0.125
Bottom	

Figure 3 presents the granulometric profiles used as input data in the numerical model.

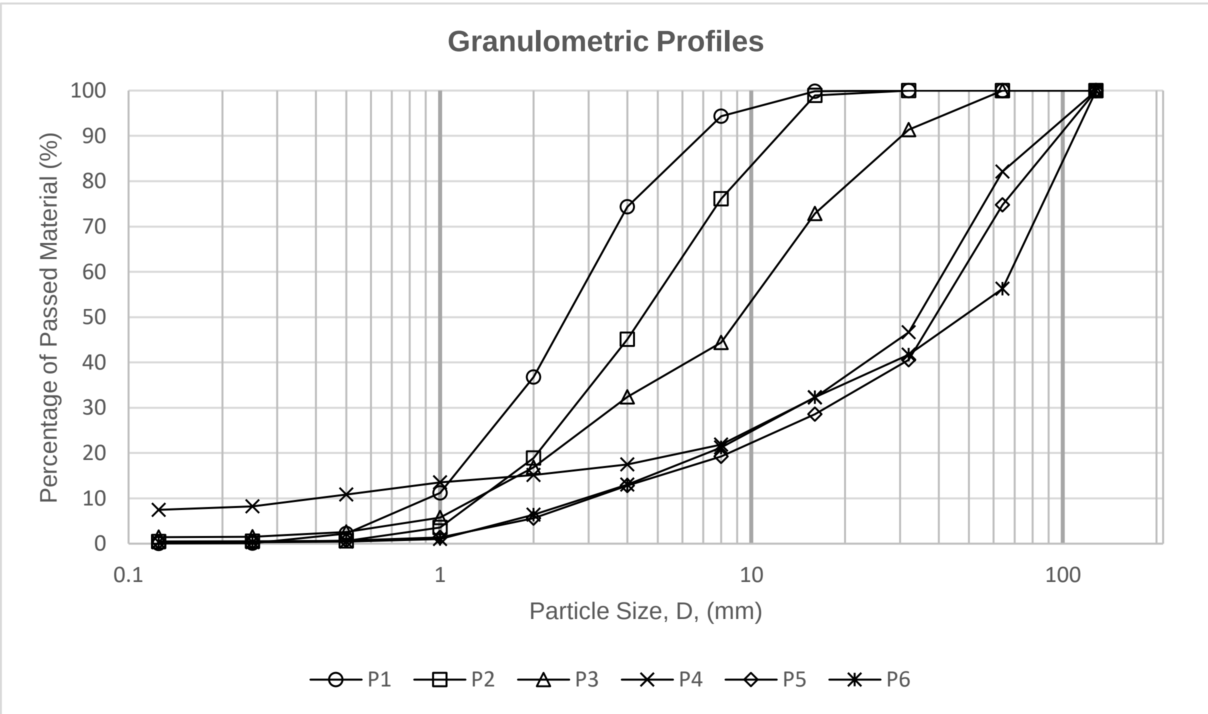

Figure 3 – Granulometric Profiles used as input data

Erro! A origem da referência não foi encontrada. presents the redefined D_{50} values and **Erro! A or igem da referência não foi encontrada.** presents the increasing coefficient between the initial and the redefined D_{50} values.

Table 9 - Redefined D_{50} values for input data

D_{50} as input data					
P1	P2	P3	P4	P5	P6
(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
2.70	4.63	9.58	35.00	40.84	50.21

Table 10 - D50's Increase Coefficient

D_{50}'s increase coefficient					
P1	P2	P3	P4	P5	P6
1.6	1.7	1.4	1.7	1.5	1.7

Not all the D_{50} values increased on a proportional way, though the differences are not significant, since the coefficient varies between 1.4 and 1.7, the granulometric profiles kept the same hierarchic order, and since these values are used as representative values, regarding the analysis of the variable granulometry.

3.4.2. FLOW

The flow data (measured in an hourly time scale), initially consisting of a flow series of 5 years of measurements, was divided into 5 flow series, each corresponding to the wet periods of each year. Each flow series corresponds to a 3 month-set of consecutive data measurements taken from the highest flow period of each year and it was used to represent the morphological changes of the river bed for each year. This study utilizes data measured in the years of 2010 to 2014. The streamflow data was summarized using several different statistics in order to better represent the complexity of the flow's variability. Table 11 presents these statistics regarding each of the flow series, namely, mean flow, standard deviation (SD), minimum flow (Min), percentile 10 (P_{10}), percentile 25 ($_{25}$), median, percentile 75 (P_{75}), percentile 90 (P_{90}) and maximum flow (Max). Some of these statistics are also presented in Figure 4, (except for the mean and standard deviation of the flow magnitude), for a better representation of the flow series. The 0^{th} and 100^{th} percentile are equivalent to minimum and maximum flow, respectively.

Table 11 - Flow Series' Values regarding some statistics

Flow Series	Mean (m3/s)	SD (m3/s)	Min. (m3/s)	P_{10} (m3/s)	P_{25} (m3/s)	Median (m3/s)	P_{75} (m3/s)	P_{90} (m3/s)	Max. (m3/s)
2010	180.0	108.9	7.3	50.2	134.9	141.5	210.3	379.9	522.6
2011	85.2	56.9	7.0	7.6	22.8	106.1	130.5	138.2	181.7
2012	9.7	9.6	7.0	7.0	7.0	7.0	7.0	11.8	116.2
2013	211.6	181.1	4.8	23.5	109.4	139.7	296.7	517.7	760.2

2014	284.7	215.6	7.0	24.4	136.7	198.9	397.2	663.1	756.3

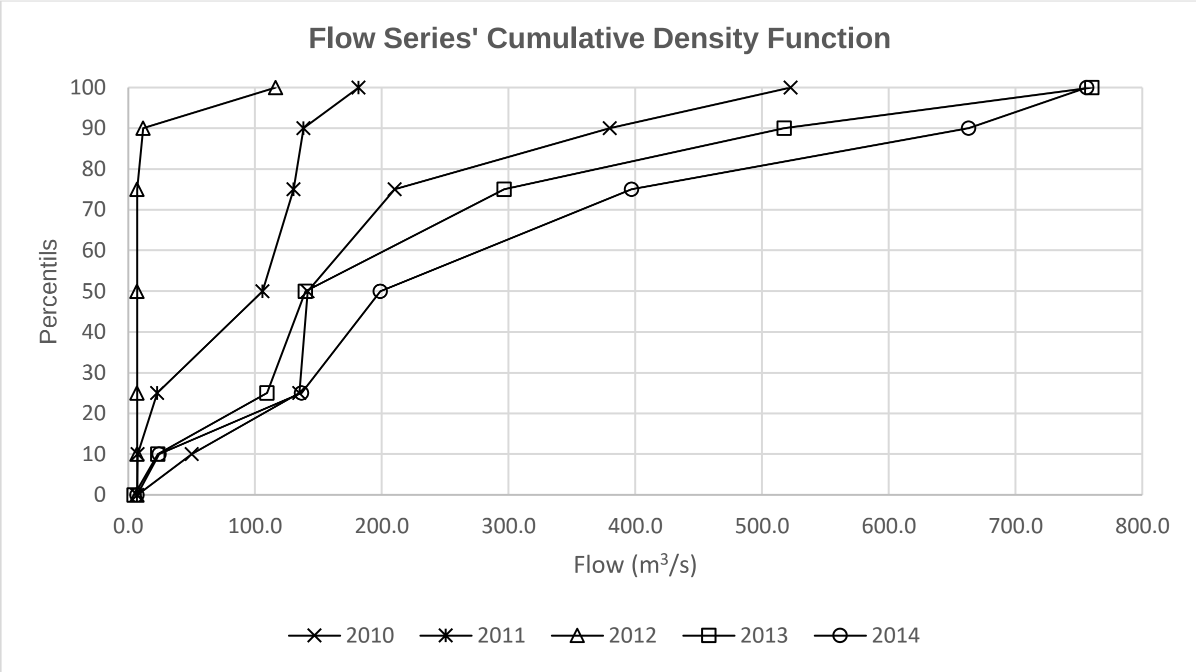

Figure 4 - Flow series cumulative density function

From Figure 4 it is possible to observe that the 2014 flow series presents the highest flow magnitude values and the flow series of 2012 presents the corresponding lowest values.

Each flow series will be represented by its respective mean flow values (presented in Table 11), given that these statistics have been observed to correctly represent the hierarchical order, observable in Figure 4. The hierarchical order of the series, from the lowest to the highest mean flow value, is of 2012, 2011, 2010, 2013 and 2014. To simplify the understanding, this hierarchical order will be represented by (S1, S2, S3, S4 and S5).

3.5. SIMULATION PARAMETERS

Apart from the data regarding the channel's geometry, flow and granulometry (which were defined based on historical records), another variable had to be defined in order to perform the numerical hydro-morphodynamic modelling, namely, bed roughness (here considered as uniform along the river bed).

Since there was no available data related to this variable for the river in cause, bed roughness was defined based on the available literature and on an initial calibration of the mean value of water level. From the literature review it was possible to see that the most common roughness value for a natural stream on a major river is of around 0.035 s/m$^{1/3}$. The initial calibration of the mean bed roughness value was based on visual observations of the water level in the normal bed, and the value obtained in the calibration was also of approximate 0.035 s/m$^{1/3}$. Thereby, this value was adopted as the mean bed roughness value for the corresponding variability range. Regarding the uncertainty surrounding the bed roughness, a range of 0.01 s/m$^{1/3}$ was considered (based on the range of values for similar channels, presented in the available literature). Accordingly, the bed roughness values considered for the Monte Carlo Simulation were 0.03, 0.032, 0.034, 0.036, 0.038 and 0.04 s/m$^{1/3}$.

Regarding the simulations' general parameters, the impact of uncertainty in contraction and expansion coefficients is not studied in the present study. These coefficients were therefore assumed to be constant, and equal to 0.1 and 0.3 (respectively), which are the commonly adopted values for a stretch of river channel without any hydraulic structures.

The boundary condition type at the downstream boundary was set to normal depth (h_n) with a friction slope of 0.001 and to bed load equilibrium conditions regarding the sediment transport.

4
METHODOLOGY

4.1. INTRODUCTION

The analysis of a study on morphodynamics' framework can have different focus. In the current study, it was decided that the focus should be on the main variables, meaning, the variables which contribute the most for the morphological change of a river bed. The objective was to analyse the variables concerning to their independency, interdependency and the overall impact on morphological behaviour by means of a stochastic modelling software. In the previous chapter has already been provided information relative to the case study, referring all the considerations made for the input data during the stochastic model creation. This chapter presents the choice of the methods, models and tools to carry out the present study, and the respective justifications for such choices.

4.2. PRIOR CONSIDERATIONS

This study was carried out considering non-cohesive sediments carried by a non-tidal lowland river with subcritical flow and fixed banks.

The studied variables are, flow, granulometry of the sediments present on the river bed, and bed roughness, since upon a literature review from several articles (Visconti, Camporeale, and Ridolfi 2010; Kasvi et al. 2014), concerning 1D model simulations, these variables seem to produce the most significant morphological change on the river bed.

These variables were inputted in a stochastic modelling software to run several simulations and obtain the variations of the river bed for different combinations of the variables' values over a 3-month period. The number of simulations is based on all the possible combinations between flow, granulometry and roughness parameters, therefore, since they consist in 5, 6 and 6 parameters, respectively, the number of simulations is 180. Each of the 5 flow parameters consists in 2160 flow measurements, corresponding to a 3 month period, each of the 5 granulometry parameters consists in a correspondent granulometric profile, and each of the 6 roughness parameters consists in a specific value within the specified range (0.01 s/m$^{1/3}$) between 0.03 and 0.04 s/m$^{1/3}$.The minimum channel elevation at the last variation stage of each cross-section was the outcome taken from each simulation.

The 1D model simulation was the chosen option, rather than a 2D model simulation, due to the short-time period given to develop this thesis, since the computational effort per individual numerical simulation is higher, if carried out in a 2D model hydraulic analysis, so it takes a long time to be computed, and due to the increment of complexity that it comes with, therefore the 180 simulations results would take too long to be obtained and analysed.

The ranges of data values were chosen thinking on the best option, considering the specific case that is being studied. The criteria were based on the characteristics of the case study (viz., geometry, location and period of the year), the available data, and in order to produce more realistic results. This means that instead of considering unique values for each parameter, were considered several values taken as one parameter, for the cases of granulometry and flow, which are based in granulometric profiles and flow series, respectively. In accordance, an existential increasement in the complexity of morphodynamics behaviour evaluation takes place, since after obtaining the river bed's elevations results from the simulations, the clarification of these variables' impact on morphodynamics and the interdependencies between them will be even more complex. For more realistic conditions, it was considered flow series and granulometric profiles to reduce the uncertainty of the input data for the stochastic model, whereas isolate values would increase the uncertainty due to the lack of realistic data. This is directly connected to the fact that a river bed presents elevation changes during diverse flood events and sediment sizes.

Bed roughness is the only variable that was obtained solely based on the available literature, since there were no available data related to this variable for the river in cause. This approach was based on the fact that the approximate roughness value for a natural stream on a major river is around 0.035. Therefore, the values considered were (0.03, 0.032, 0.034, 0.036, 0.038 and 0.04).

In the remainder of this thesis, the sections independent sensitivity analysis and the joint sensitivity analysis were created to distinguish between the 2 different steps of the analysis. Both analyses use different software, which are presented on the next subchapter. The calculation methods used on both analyses are presented in the remainder of this chapter. In the analysis of the results, the representative values of each variable are presented, for a better understanding of the results, as:

- Flow - The mean values of each flow series (viz., 9.7, 85.2, 180, 211.6 and 284.7 (m^3/s), from S1 to S5 respectively);
- Granulometry - The D_{50} of each granulometric profile (viz., 2.70, 4.63, 9.58, 35.00, 40.84 and 50.21 (mm), from P1 to P6, respectively);
- Bed roughness - The original values, the ones previously considered.

4.3. SOFTWARE

4.3.1. SIMULATION SOFTWARE

For the study of the morphological behaviour of a river bed exists many software available to carry out different simulations. Several software, such as MIKE11 and HEC-RAS are used for: (a) one dimensional (1D) hydrodynamic and morphodynamic analysis and (b) the simulation of hydrodynamic conditions in river channels. The chosen software was HEC-RAS since it is lectured in the present course.

The 1D model has as main characteristics: a) flow velocity is simulated solely in the longitudinal direction, b) simulated flow can be permanent and non-permanent (in the present study), c) the channel is represented by its respective cross-sections and d) where the flow speed is represented by its average value.

Within the 1D model, and between steady flow, unsteady flow and quasi-unsteady flow, the latter was the chosen option since it is only used for sediment studies. The quasi-unsteady flow model simplifies hydrodynamics, representing a continuous hydrograph with a series of discrete steady flow profiles. HEC-RAS computes hydraulics each time step before it routs sediment or updates cross-section, and it keeps flow constant for each flow record, computing transport over flow record duration.

Upon the respective simulations for a 3-month period, a first view of the results was seen before a thorough analysis, and an example of it is the 3D cross-section plot shown in Figure 5.

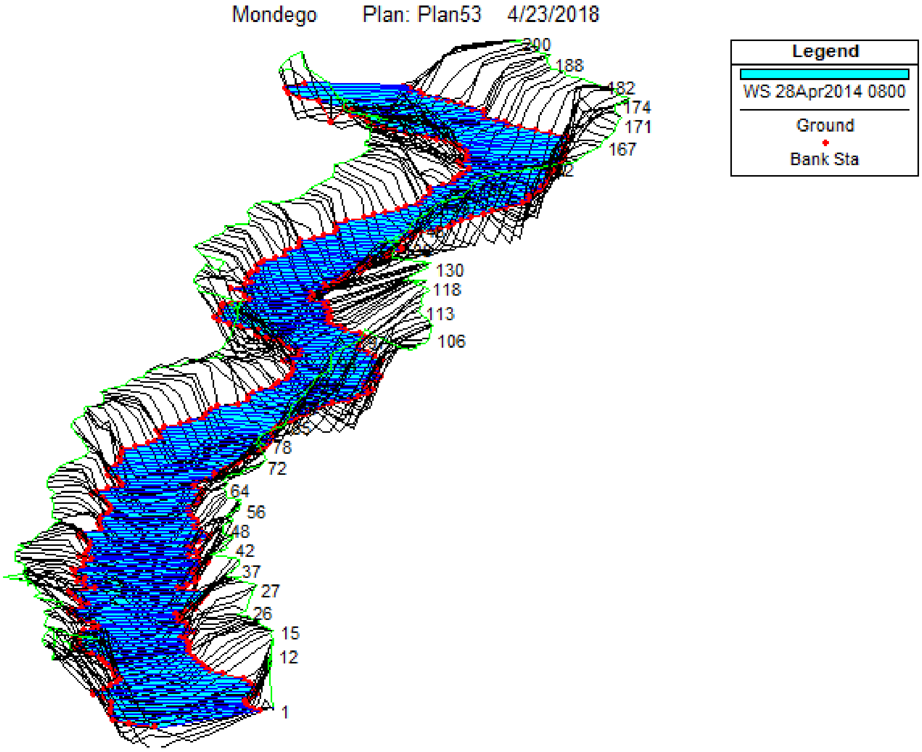

Figure 5 - Example of a 3D Cross-Section Plot of a Rio Mondego's Stretch

The 3D cross-section plot only presents the variance of flow over the respective 3-month period plotted with the unaltered cross-sections' elevation, though we were able to visualize the variations of the elevations as presented n Figure 6.

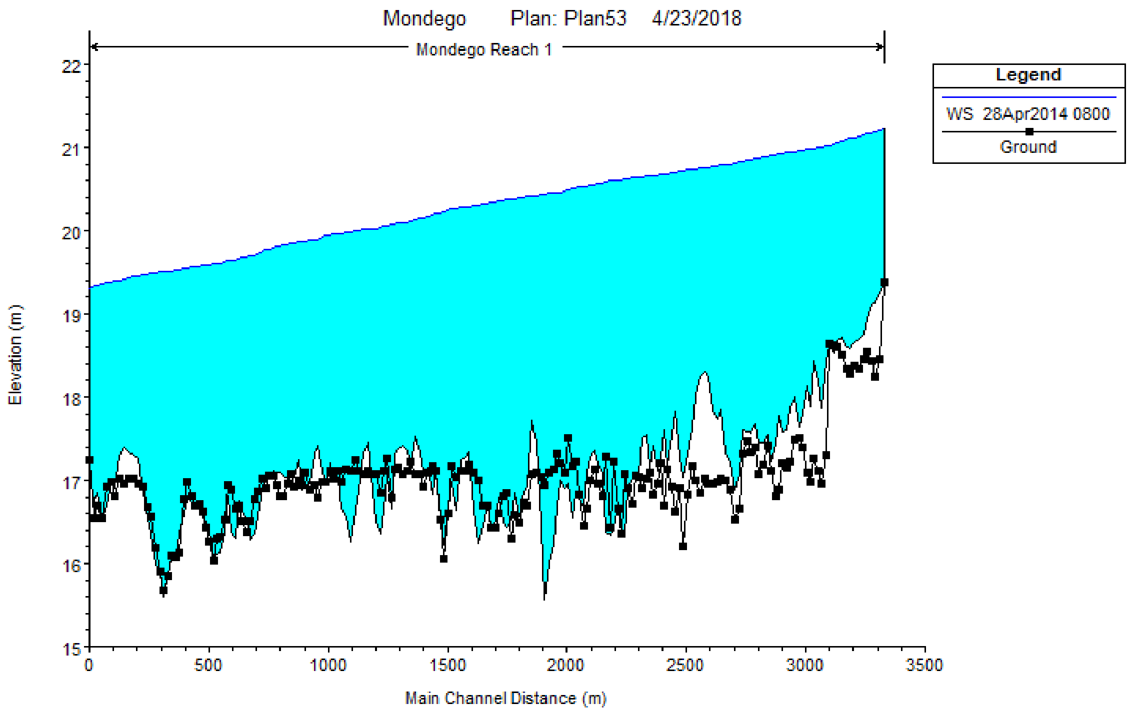

Figure 6 - Profile Plot Example of a Simulation of a Rio Mondego's Stretch

The observation of the results in a visual animate form allows the user to analyse which parts of the channel suffer the most significative changes in elevation, to observe the flood event comparatively to these changes and, possibly, to analyse if there is something wrong with the input data, for example, the boundary conditions could certainly be a problem, and therefore it could be easily detected.

4.3.2. Software For Output Data Treatment

EXCEL was the software used for the treatment of the output data on the primary results and the independent sensitivity analysis present on sections 5.1 and 5.2. ↓, respectively.

4.3.3. Statistical Software

The adopted software for the statistical analysis was RStudio (software based on R language), which was used for the joint sensitivity analysis present on section 5.3. ↓. RStudio is a software used for data processing, and it was used to generate graphs showing the interdependency between the analysed variables for specific statistics based on the rearranged (on EXCEL) outcome data from the simulations on HEC-RAS.

4.4. Calculation Methods Used On the Analyses

After obtaining the elevations from the 180 simulations, the output data was analysed from an overall perspective (section 5.1. ↓), showing the general results, concerning to the number of simulations of each cross section that either had erosion or sedimentation as outcome, and the extreme values, both for erosion and sedimentation, from all the simulation results present in each cross section. This was a way of presenting the main characteristics of the overall results.

After this prior analysis, a thorough analysis for the understanding of the independent impact that each variable had on morphodynamics behaviour of the river bed's elevations (section 5.2. ↓) was carried out, followed by the joint sensitivity analysis, which presents the relative total impact of each variable on morphodynamics and the interdependencies between them based on several statistics (section 5.3. ↓).

4.4.1. Independent Sensitivity Analysis

The independent sensitivity analysis refers to the analysis of the relationship between each variable and morphodynamics, showing the effect that each variable has on morphodynamics by evaluating the linearity or non-linearity, the magnitudes of the river bed's variations. Therefore, 4 aspects of morphological change were additionally considered on this evaluation, namely:

- Erosion (mean of the negative values of the river bed's variations (i.e., comparing to the initial elevations));
- Sedimentation (mean of the positive values of the river bed's variations (i.e., comparing to the initial elevations));
- Balance (mean of all the river bed's variations, presenting an equilibrium between erosion and sedimentation);
- Total Impact (mean of the river bed's variations turning all variation values into absolute values).

These aspects were considered important since they can give a better characterization to the variables for a better analyse.

4.4.2. Joint Sensitivity Analysis

For the current analysis, RStudio was used for the statistical calculations, which resulted in a graphical analysis.

The joint sensitivity analysis is meant to represent the interdependencies between each variable (considering the variation of the absolute mean of the river bed's change regarding each variable) and the overall effect that each variable has on morphodynamics, providing a relative measurement of their importance. Several statistics of the river bed's variations were analysed for a better representation of the results, namely:

- M (Mean);
- SD (Standard Deviation);
- Q25 (Quantile 25);
- Q75 (Quantile 75);
- Q80/Q20 (ratio between Quantile 80 and Quantile 20).

If Abs (Absolute) appears followed by a statistic abbreviation it means that the statistic is based on absolute values of the elevations' variation.

These statistics were calculated for the observation of the interdependencies between the variables along with the statistic's value, and for the obtention of each variable's overall importance (S_{Ti}) according to the magnitude of each statistic, related to the variations in elevation caused by a certain variable.

The visual analysis of the relative interdependencies between the variables, regarding bed level variation (ΔH) and the formula in Eq. (4.1) that calculates the total effect index (S_{Ti}), are ways of performing the sensitivity analysis of the results in terms of variance-based sensitivity measurements. S_{Ti} is the easiest way to represent the importance of uncertainty variable X for the output Y because it quantifies the sensitivities of the previous mentioned statistics calculated for each variable in terms of the river bed's changes for an overall measurement of the morphological behaviour.

$$STi = \frac{\mathrm{E}[\mathrm{Var}(Y|Xi)]}{\mathrm{Var}(Y)} = 1 - \frac{Var[E(Y|Xi)]}{Var(Y)}\ , where\ Y = \Delta H\ and\ i\ \in X = \{n, D50, Q\} \tag{4.1}$$

The total effect indices calculation was divided in 2 steps, being on the first one considering the statistics of the real variation signs' values of the elevations (i.e., for erosion (-) and sedimentation (+)) and the second one considering the absolute signs' values of the elevations.

The maximum values of each flow series were not considered (instead of the mean values) because the spacing between parameters would be too far from an equality, and therefore, when assessing the relative interdependencies between each variable (regarding bed level change) by observing the respective charts, the spacing between each parameter is relevant for a good understanding of the right angles that the contour lines do with the axis.

The considered better representative graphs are presented to show the interdependencies between the variables, analysing their pairwise independency and the parameters of each one (i.e., analysing the growth of the variables in comparison to the growth of the outcomes (statistics relative to the elevation's variation)). These graphs are assessed by observing the spacing between contour lines and the angles that they do with both axes. If the contour lines are perpendicular to a specific axis, it means that the respective values of the variable, represented on the axis, presents a higher impact on the variation of the plotted mean values for the given values of the other variable under analysis. If contour lines are parallel to a specific axis, it means that the respective values of the variable, represented on the axis, don't induce changes on the respective mean values for the given values of the other variable under analysis. If there is a small spacing between contour lines and a high level of linearity along the axis, the complexity level on the relationship between the variables will be low. If otherwise (high spacing between variables and non-linearity) the complexity level on the relationship between variables will be high.

5
NUMERICAL MODELLING – RESULTS' ANALYSIS

In the present chapter primary results are plotted before a thorough analysis and a proper discussion of the results obtained on the analyses. The analysis of the simulation's results was divided in 2 steps, the first one is the independent sensitivity analysis and the second one is the joint sensitivity analysis.

Many studies were carried out with the purpose of better understanding morphodynamics behaviour, and the balance between erosion and sedimentation was evaluated since these studies were carried out for a long-time period and the effect of morphodynamical evolution (concerning the balance effect present on rivers) has a major impact within time periods wider than 3 months. Since these simulations were carried out for a short-time period, that aspect is not relevant, though it is also considered during these analyses for a better representation of the outcomes.

The primary results simply refer to the values of all the simulations. Here the assessment is mostly superficial, analysing some of the main characteristics of the results, such as the extreme values of each cross-section (in terms of the variation of the river bed's elevations), regarding erosion and sedimentation, and the lack or abundance of erosion and sedimentation on each cross-section considering all the 180 simulation's results. These results must be assessed thoroughly for a better understanding of the sediments' behaviour considering the studied variables. Therefore, and in addition to the previous analyses, flow, bed roughness and granulometry are studied separately to evaluate the effect that each value (viz., 5 different flow series, 6 different bed roughness and 6 different granulometric profiles) of each variable has in terms of the morphodynamics' sensitivity when considering the mean values of the elevations' variations of the river bed. Subsequently, the extreme values are first plotted, followed by the independent sensitivity analysis and the joint sensitivity analysis.

Each variable is represented by using reference values. Granulometry is represented by D_{50} values of the granulometric profiles, flow is based on the mean value of each flow series, and bed roughness is based on its original values (i.e., the ones previously considered).

The independent sensitivity analysis refers to the analysis of the relationship between each variable and morphodynamics, showing the effect that each variable has on morphodynamics by evaluating the linearity or non-linearity and the magnitudes of the river bed's variations. Therefore, 4 aspects of the morphological change were considered on this evaluation, namely:

- Erosion (mean of the negative values of the river bed's variations (i.e., comparing to the initial elevations));
- Sedimentation (mean of the positive values of the river bed's variations (i.e., comparing to the initial elevations));

- Balance (mean of all the river bed's variations, presenting an equilibrium between erosion and sedimentation);
- Total impact (mean of the river bed's variations turning all variation values into absolute values).

Theses aspects, defined relative to each variable, were quantified, according to mean values of the river bed's variations. This evaluation is intended to assess, regarding each aspect of morphological change, the linearity, the magnitude and the effect of each variable in morphodynamics.

The joint sensitivity analysis, is meant to represent the inter-dependencies between each variable (considering the variation of the absolute mean of the river bed's change regarding each variable) and the overall effect that each variable has on morphodynamics, providing a relative measurement of their respective importance. In this step, several statistics of the river bed variations were analysed for a better understanding of the results (viz., mean, standard deviation, 1st quartile, 3rd quartile and the ratio between quantile 80 and quantile 20), considering the original values and the absolute values of the elevations' variation.

5.1. PRIMARY RESULTS

The results of the 180 simulations concerning to the variation of the topographic elevations of the river bed, were plotted in Figure 7.

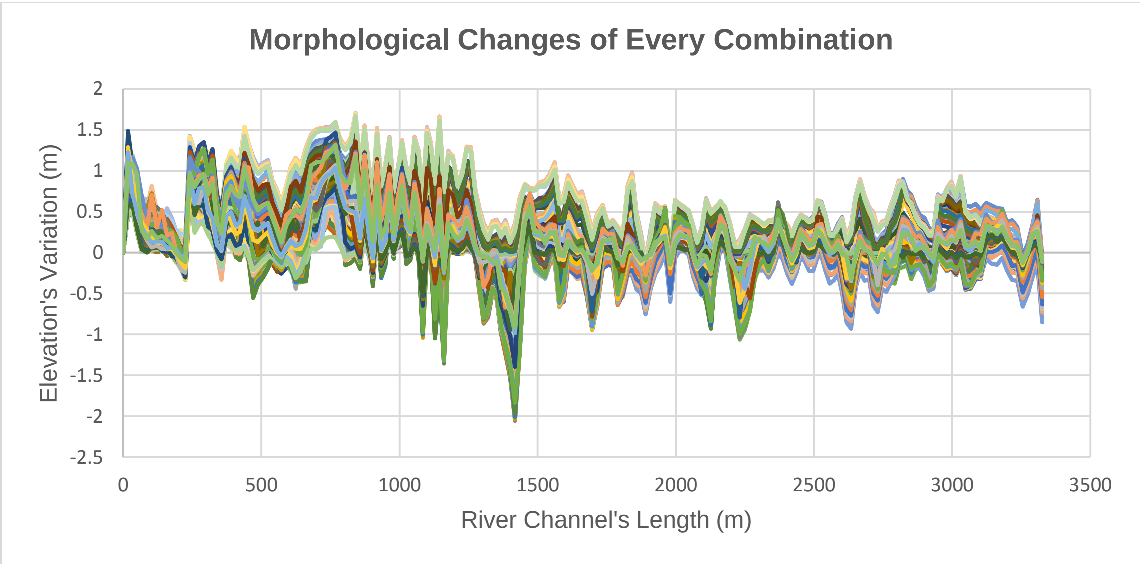

Figure 7 - Morphological changes of every combination, considering the values of the cross-section elevations' variation of the 180 simulation results.

As can be seen in Figure 7, the river bed has a tendency for sedimentation, which is more visible in the upstream cross-sections of the river stretch, until approximately 1250 meters downstream. Forward from that point, sedimentation clearly has a lower impact than erosion, that lasts for up to 250 meters (approximately), and from that point until the last cross-section, the balance between erosion and sedimentation takes place. From the 180 simulations and taking in count every variation on the initial elevation of each cross-section it was possible to calculate the ratio between erosion and sedimentation on the whole stretch, which is equal to 0,54 and means that erosion was found in approximately half of the simulation results.

Results are presented in Figure 8 regarding the most prominent tendency in each cross-section, considering erosion and sedimentation in each simulation.

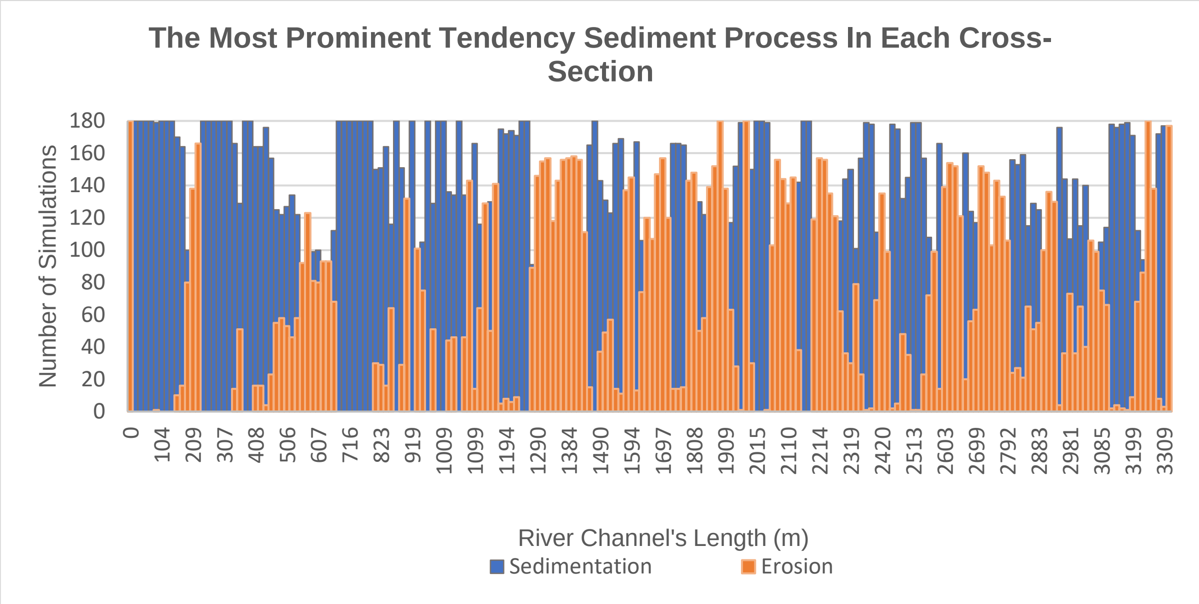

Figure 8 - The Most Prominent Tendency Sediment Process in Each Cross-Section; Lack of a process means abundance of another.

As seen in Figure 8, sedimentation is more widely present than erosion in the simulation results.

Figure 9 presents the highest and the lowest variations in river bed's elevations (relative to the initial elevations) representing the maximum range of the potential bed change.

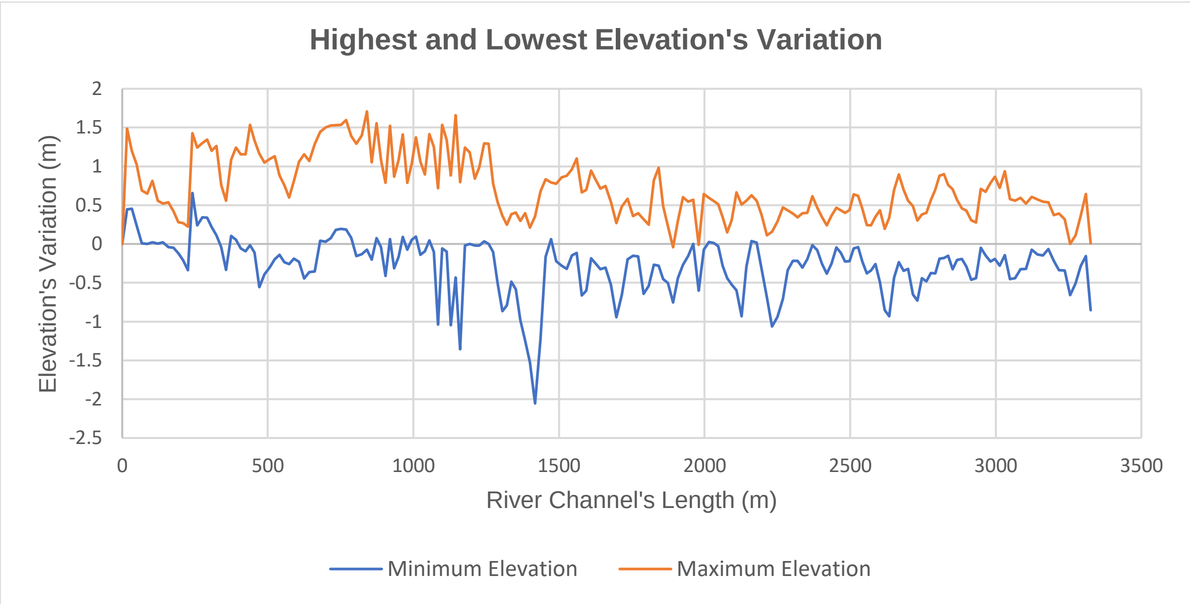

Figure 9 - Extreme Variation Values due to erosion and sedimentation in each cross-section.

The highest variation values are 2,05 meters and 1,71 meters for erosion and sedimentation, respectively. As seen in Figure 9, sedimentation clearly shows an abundant number of cross-sections in which the value of the elevations' variation is proximate to the highest values (already pointed out) in comparison to erosion.

5.2. Independent Sensitivity Analysis

In order to know which parameter of each variable influences topography the most, the mean variations of the channel's initial elevation values (with regard to each parameter of the respective variable) were plotted for a better representation of sedimentation and erosion.

5.2.1. Flow

The mean elevation's variation of each of the 5 flow parameters were plotted in Figure 10.

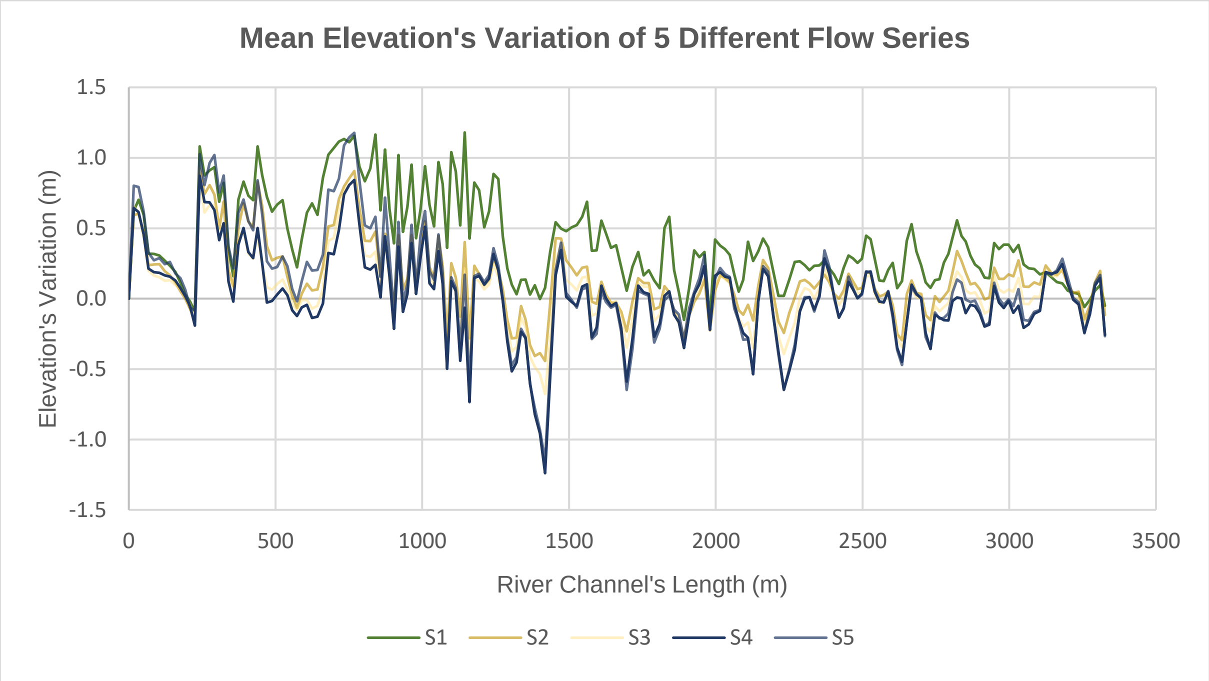

Figure 10 - Mean Elevation's Variation of 5 Different Flow Series showing a comparison between them, with respect to bed changes.

As seen in Figure 10, S1 is the one which contributes the most for sedimentation and S4 and S5 are the ones which contribute the most for the erosion process. The highest differences between parameters (in terms of mean elevation's variations) go up to 1,32 meters.

Figure 11 presents the 4 aspects (previously mentioned at the beginning of the current chapter) regarding the evaluation of flow and considering the mean flow value of each flow series.

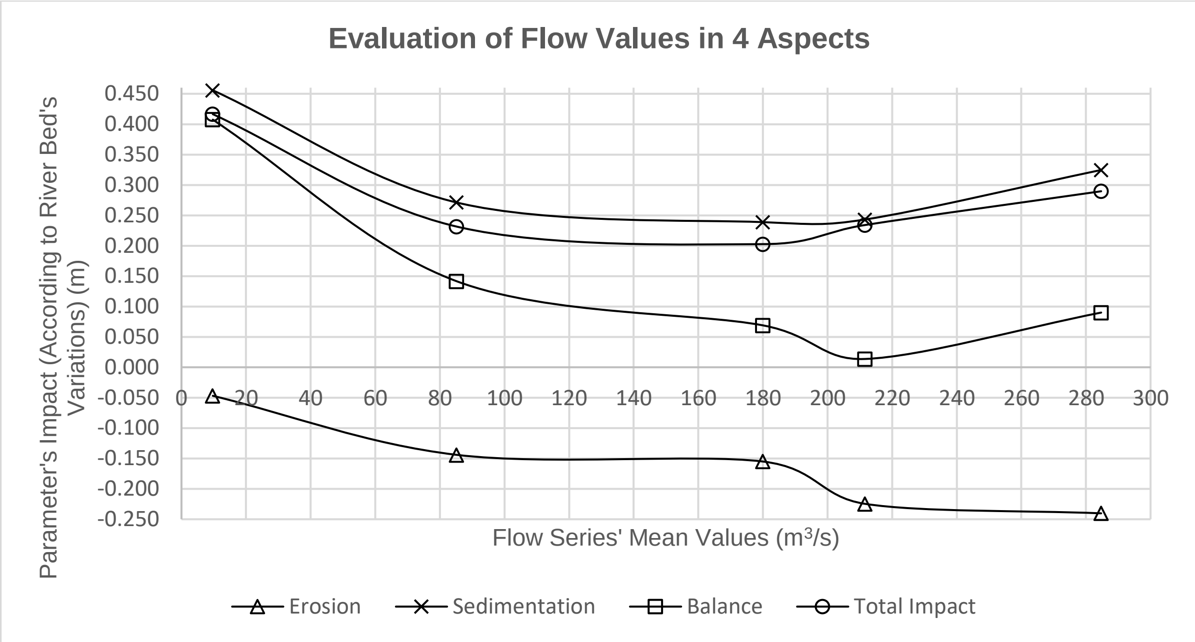

Figure 11 – Evaluation of Flow Values in 4 Aspects, presenting the overall results (over the full length of the river channel)

As can be seen in Figure 11, flow follows a hierarchic order in the erosive aspect. Flow values present a similar effect between sedimentation and total impact, presenting both a monotonic effect.

5.2.2.Bed ROUGHNESS

The mean elevations variations of each of the 6 bed roughness' parameters were plotted in Figure 12.

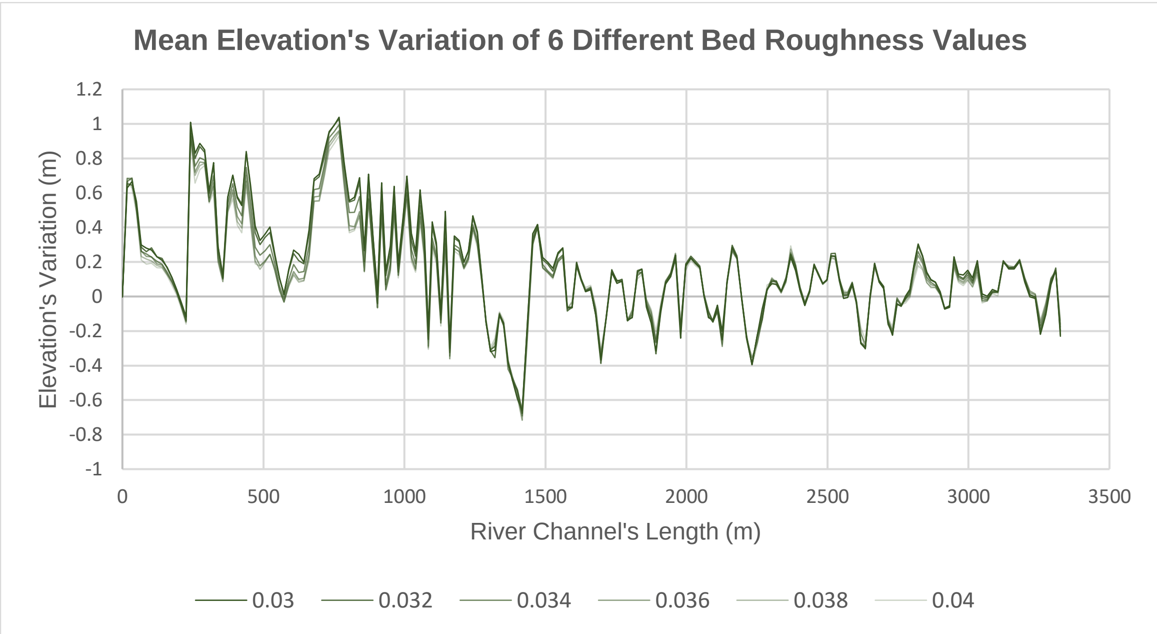

Figure 12 - Mean elevation's variation of 6 different bed roughness values showing a comparison between them, with respect to bed changes.

Figure 12 shows that the bed roughness' variation makes a small difference on topography. And in the first kilometre is seen that the highest differences between roughness' values (in terms of mean elevations' variation) go up to 0,23 meters.

Figure 13 was plotted for a better understanding of the difference between each parameter, showing the mean variation results of the highest and lowest bed roughness' parameters.

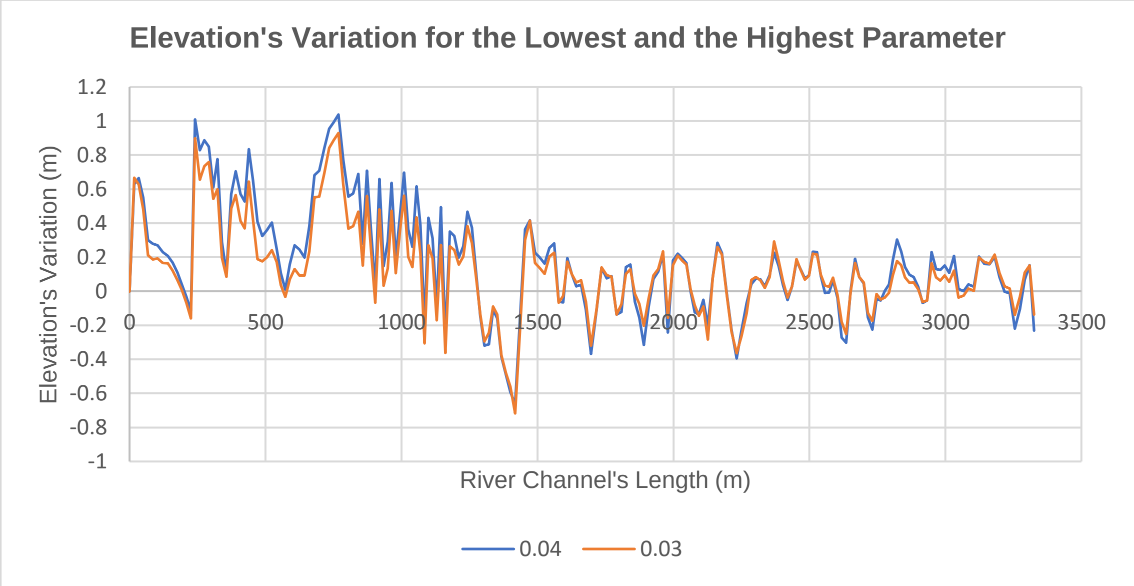

Figure 13 - Mean Elevation's Variation of the highest and lowest bed roughness values showing a comparison between them, with respect to bed changes.

In Figure 13 is displayed the variation of the river bed's elevations of the lowest and the highest bed roughness' value, showing that the impact caused on morphodynamics is not strictly linear with the growth of the roughness value. Figure 14 presents the 4 aspects (previously mentioned at the beginning of the current chapter) regarding the evaluation of bed roughness.

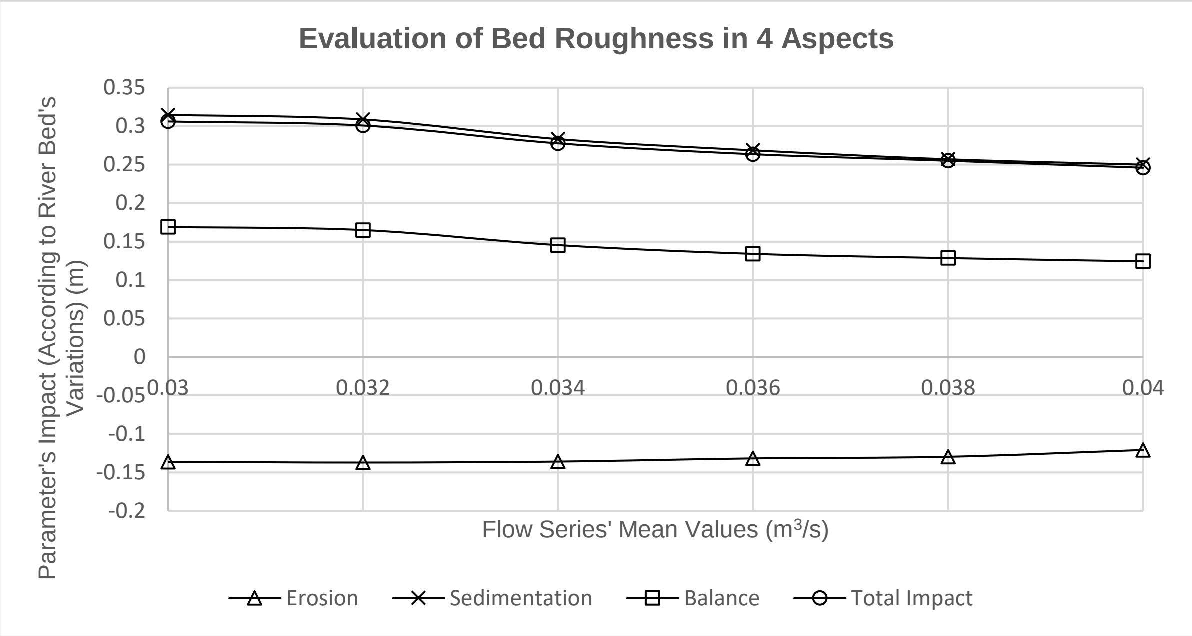

Figure 14 – Evaluation of Bed Roughness in 4 Aspects, presenting the overall results (over the full length of the river channel)

As can be seen in Figure 14, bed roughness follows a hierarchic order, and a linearity does exist on the aspects of sedimentation, balance, total impact, and mainly on erosion. Bed roughness' values present a similar effect between sedimentation and total impact.

5.2.3. Granulometry

Figure 15 presents the elevation's variation for each granulometric profile.

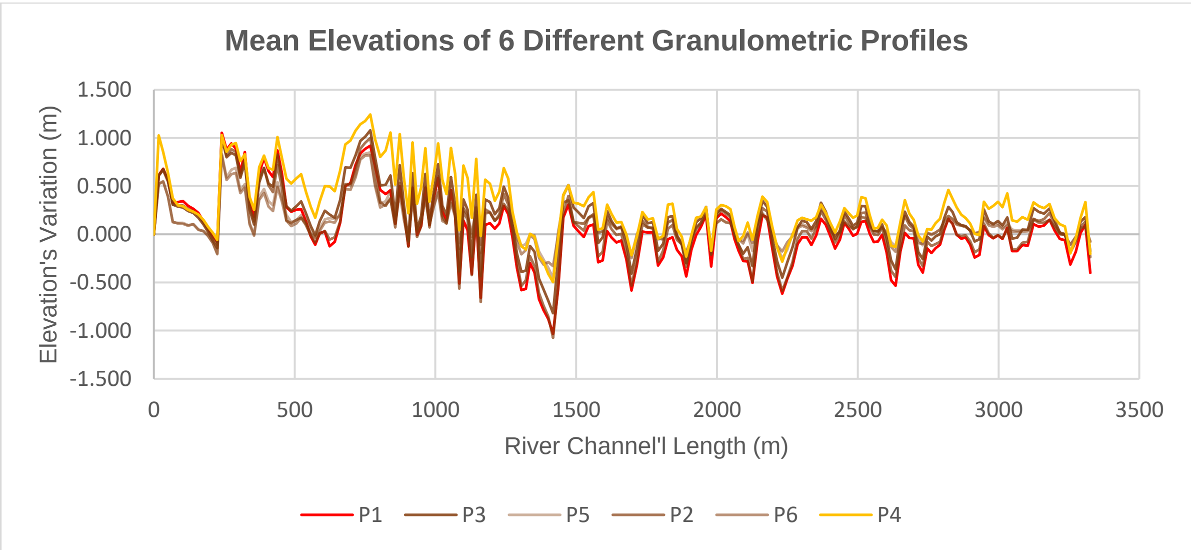

Figure 15 - Mean elevation's variation of 6 different flow series showing a comparison between them, with respect to bed changes.

Profile 4 has the highest mean elevation's variation value of 1,24 meters on sedimentation and profile 2 and 1 have the lowest values of 1,07 meters and 1,03 meters, respectively, on erosion. The highest differences between granulometric profiles (in terms of mean elevations' variation) go up to 0,74 meters.

Figure 16 presents the 4 aspects (previously mentioned at the beginning of the current chapter) regarding the evaluation of granulometry and considering the D_{50} value of each granulometric profile.

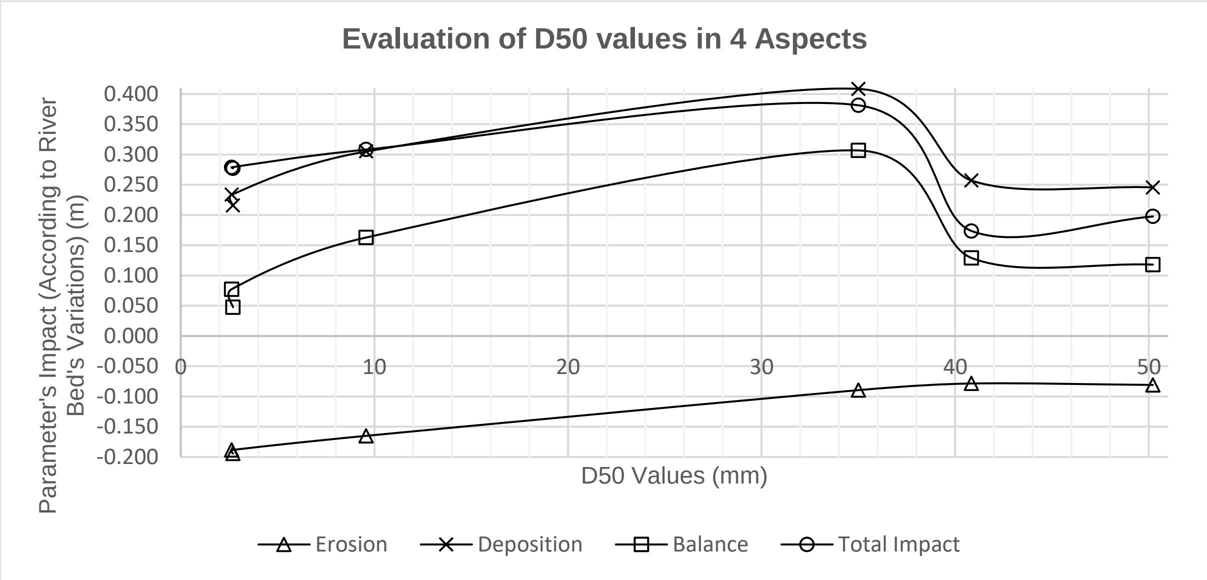

Figure 16 – Evaluation of D_{50} values in 4 Aspects, presenting the overall results (over the full length of the river channel)

As can be seen in Figure 16, a monotonic effect does exist in the different aspects of granulometry, and with respect to erosion, the monotonic effect is also proximate to a linearity. This is the only aspect in which the hierarchic order is respected, from the lowest to the highest D_{50} value with a continuous decrease on its impact. In the paper (Nabi, De Vriend, and Mosselman 2012) is observed that the grain size has a significant effect on the drag's hysteresis. They state that the larger the diameter, the larger the hysteresis. These results present a similar effect, regarding erosion.

5.3. Joint Sensitivity Analysis

The joint sensitivity analysis was based on HEC-RAS's outcomes of the stylized channel (viz., variations of the river bed at the end of the simulated time-period) and on the redefined parameters for each variable, taking these parameters as a reference on the statistical analysis' calculations.

The total effect indices calculation was divided in 2 steps, being on the first one considering the statistics of the real variation signs' values of the elevations (i.e., for erosion (-) and sedimentation (+)) and the second one considering the absolute signs' values of the elevations. The statistics considered follow the abbreviations:

- M (Mean)
- SD (Standard Deviation)
- Q25 (Quantile 25)
- Q75 (Quantile 75)
- Q80/Q20 (ratio between Quantile 80 and Quantile 20)

If Abs (Absolute) appears followed by a statistic abbreviation it means that the statistic is based in absolute values of the bed level variation.

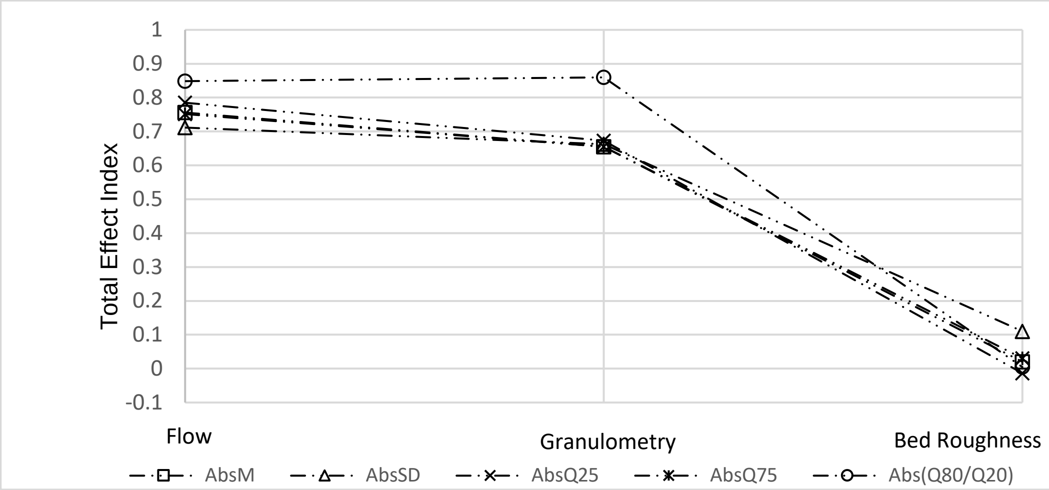

Figure 17 - Total Effect Index values of 3 different variables exhibiting the overall relative importance of these variables to the channel's morphodynamical behaviour regarding the elevations' variation absolute values.

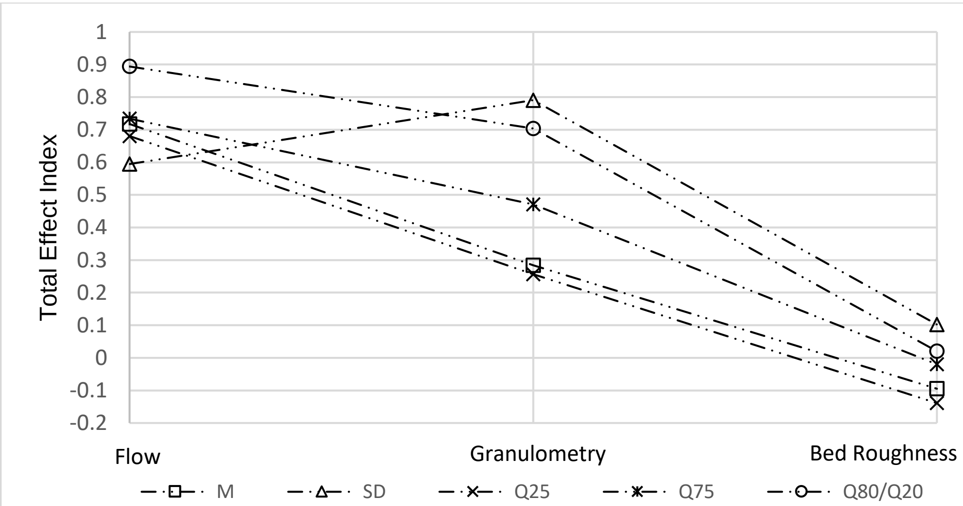

Figure 18 - Total Effect Index values of 3 different variables exhibiting the overall relative importance of these variables to the channel's morphodynamical behaviour regarding the elevations variation.

In Figure 17, with exception to Abs(Q80/Q20), the statistics show, by decreasing order of relative importance to the channel's morphological behaviour (based on total effect index), flow, granulometry and bed roughness, whilst in Figure 18 the standard deviation (SD) shows a different sequence (viz., granulometry, flow and bed roughness), equal to the sequence of Abs(Q80/20). M and Q25 present the total effect indices more proximate to a linearity between the different variables. AbsM was considered to be the most relevant statistic since it considers the mean river's bed changes without differentiating the sedimentation from erosion, focusing on the importance of those changes in magnitude without giving importance to the specific process in cause.

The next Figure 19, 20, 21, 22, 23 and 24 are presented to show the interdependencies between the variables, analysing their pairwise independency and the values of each one (i.e., analysing the growth of the variables in comparison to the growth of the statistics relative to the elevation's variation).

These figures are assessed by observing the spacing between contour lines and the angles that they do with both axes. If the contour lines are perpendicular to a specific axis, it means that the respective values of the variable, represented on the axis, presents a higher impact on the variation of the plotted mean values for the given values of the other variable under analysis. If contour lines are parallel to a specific axis, it means that the respective values of the variable, represented on the axis, don't induce changes on the respective mean values for the given values of the other variable under analysis. If there is a small spacing between contour lines and a high level of linearity along the axis, the complexity level on the relationship between the variables will be low. If otherwise (high spacing between variables and non-linearity) the complexity level on the relationship between variables will be high.

From the different statistics in analysis, AbsM and SD were the only statistics displayed on the inter-dependencies analysis since the interdependencies analysed on the other statistics, with exception to Abs(Q80/Q20), showed similar results to AbsM and, regarding SD, exists a different hierarchy order of the variables' overall importance as previously mentioned. The results relative to Abs(Q80/Q20) were not displayed due to the extreme complexity of the interdependencies between the variables. There was a too high spacing in between the contour lines and only a few existed, thereby it shows that the complexity present on the interdependencies between the variables is so high that the graph could not be thoroughly analysed. Figure 19, 20, 21concern to the AbsM and Figure 22, 23 and 24 concern to the SD, following both figure groups the same sequence, regarding to the variables analysed.

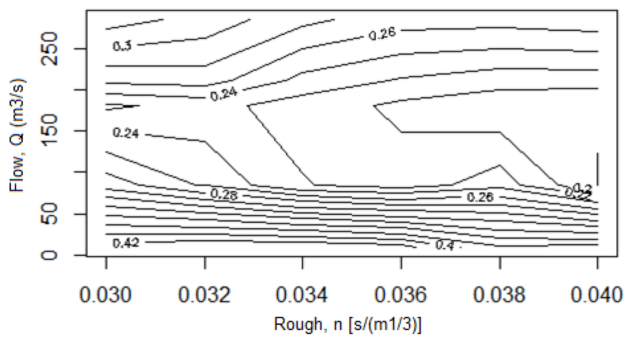

Figure 19 - Relative Interdependencies Between Flow and Roughness considering the AbsM statistic.

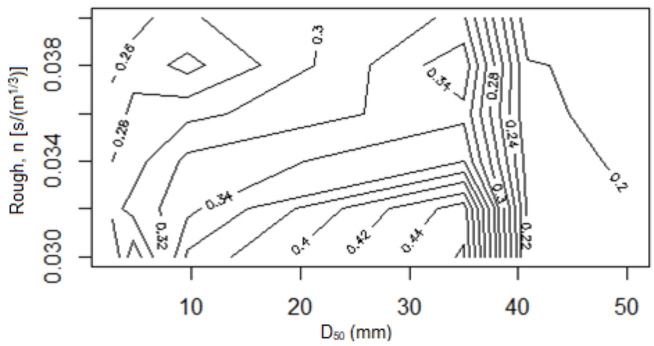

Figure 20 - Relative Interdependencies Between D_{50} and Roughness considering the AbsM statistic.

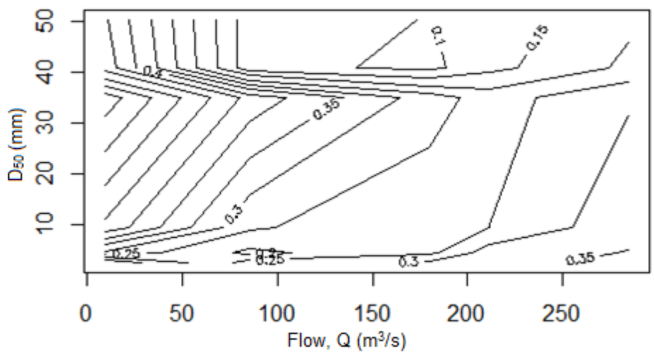

Figure 21 - Relative Interdependencies Between D_{50} and Flow considering the AbsM statistic.

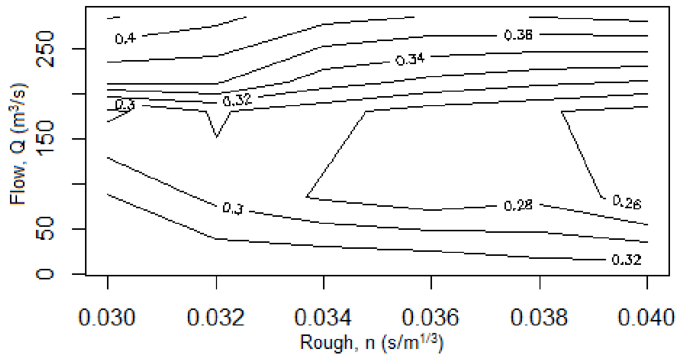

Figure 22 - Relative Interdependencies Between Flow and Roughness considering the SD statistic.

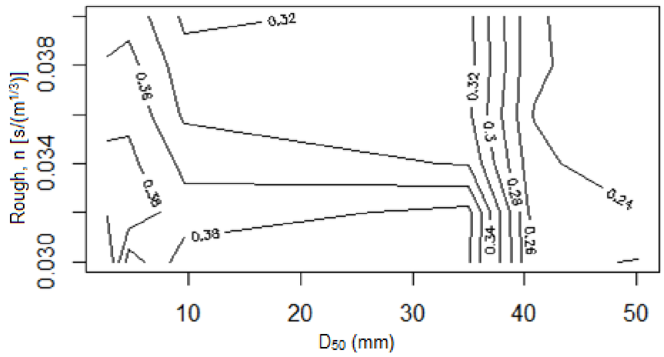

Figure 23 - Relative Interdependencies Between D_{50} and Roughness considering the SD statistic.

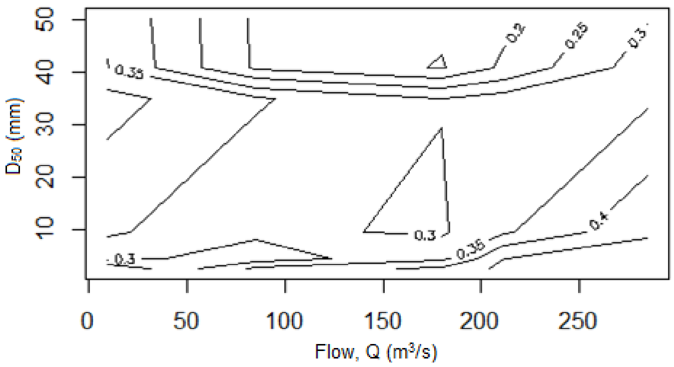

Figure 24 - Relative Interdependencies Between D_{50} and Flow considering the SD statistic.

By observing the previously Figure 19, 20, 21, 22, 23, 24 , the main general aspect noticed is the high complexity level (in interdependency terms) between the D_{50} and roughness in Figure 20 and 23 since the contour lines only follow a linearity for high D_{50} values and the same stands for the spacing between them, which is small only for high D_{50} values. In addition, another general aspect noticed is the high difference between Figure 21 and 24. They both study the same variables (viz., flow and granulometry) but since they analyse different statistics the complexity suffers a significative change.

In Figure 19 it is possible to observe that the contour lines have small spacing in between, for low flow values, and a high level of linearity along the roughness axis, therefore the complexity level present in the relationship between these variables is low. In addition, the angle that the contour lines do with the flow axis is near 90º, so the importance of flow to the morphological change, in comparison to roughness, is high. As for Figure 22, relative to standard deviation, the same analysis is pointed out the spacing between contour lines for low flow values is not so small, thus increasing the complexity level.

In Figure 20 it is possible to notice, as previously mentioned, that a possible linearity only exists for high D_{50} values and the same goes for the small spacing between contour lines, therefore, the complexity level present in the relationship between these variables is high when not considering high D_{50} values. It is also noticed that granulometry has a higher impact than roughness for high D_{50} values since the angle that the contour lines do with the D_{50} axis is near 90º. Figure 23, relative to standard deviation, presents similar results.

In Figure 21 it is observed that the complexity level present in the relationship between the variables is not high, for flow values up to 100 m^3/s, due to the high level of linearity and the small spacing between contour lines. It is also noticed that the two variables (viz., flow and granulometry) have similar interdependencies, since the angle that the contour lines do with the respective axis is near 45º. Though, from the total effect index we know that the result, relative to AbsM, shows a small higher level on the overall importance on flow, in comparison to granulometry. Figure 24, relative to standard deviation, presents a very different pattern in contour lines, since they present high spacing in between, as for linearity, it doesn't change much from what was observed in Figure 21, though, the complexity level of the interdependency between these two variables is high.

5.4. DISCUSSION

From what was observed in the results, the magnitude of these morphological changes of the river bed can reach up to 2.05 metres, which is unusually high for the simulated river channel, however this value is purely theoretical (obtained from a numerical model) and some variables' combinations may reach beyond the reasonable values' range.

Based on the results obtained in the independent sensitivity analysis, it is possible to verify that flow presents the highest importance on morphodynamics and that bed roughness has the lowest importance, whereas granulometry can be considered as of intermediate importance to morphodynamics. One aspect that supports the previous sentence is the fact that in terms of maximum morphological changes of the river bed (relative to the differences between the variable's values), flow presents the highest mean value of 1.32 meters, granulometry presents a mean value of 0.74 meters and bed roughness presents the lowest mean value of 0.24 meters. Bed roughness presents the most linear relationship with bed level change, regarding all of the 4 different aspects analysed.

From the joint sensitivity analysis, it is possible to conclude that flow has the most importance on the overall morphodynamics (considering all of the statistics), even though for two of the statistics (viz., SD and Abs(Q80/Q20)) granulometry produced an overall larger effect in bed level change. The statistic SD not however irrelevant, even though it doesn't imply a higher morphological change, it does represent an aspect of morphodynamics (i.e., its irregularity). If higher deviations relatively to the mean are produced, then it means that the bed level variations are less continuous and thus more irregulars. The statistic Abs(Q80/Q20) presents a relative importance of the variables relative to the ratio between a low and a high bed level change, in which granulometry is of greater importance than flow.

Overall, from both analyses it is possible to verify that flow presents the highest impact on morphodynamics, therefore it is the variable of most importance when studying the river bed changes, followed by the importance of the granulometry, which can, in certain aspects of morphodynamics be of great relevance. It was also observed that, for this case study, bed roughness presents a smaller impact on morphodynamics, i.e., it has the least importance to fluvial morphodynamics. Granulometry showed a medium importance on the independent sensitivity analysis and a medium/high importance on the joint sensitivity analysis. The results show an increasing importance from bed roughness to granulometry and flow in terms of the absolute overall bed level change (total impact) (≈ 1%, 46% and 53%, respectively). Other studies, such as (Van Vuren 2005; Oliveira and Maia 2018) show that granulometry is of a low importance comparatively to bed roughness, though this study presents the opposite. In these two studies the values taken for each variable were not based on real field data, thereby having a different range, a more linear variables' set and an equally spaced interval between the values taken for each variable. The considered values for each variable can change the whole outcome, that's why morphodynamics it's still under a high level of uncertainty.

6
CONCLUSIONS

As referred in the Introduction (chapter 1) the objectives of this thesis were (1) to clarify the nature of the relationship between a river bed's morphodynamical evolution and the variables most important to its definition, in the independent and joint way of analysis (so that the interdependencies of the variables in terms of their effect on morphological changes are taken into consideration), and (2) to present (graphically) and quantify the relative sensitivity of morphodynamics to the different variables analysed.

This chapter presents conclusions relative to the analyse of the results, regarding, the comparison between possible different outcomes (in an overall and regarding each variable), the results' relevance to future studies (explaining to what extent they might be relevant), the veracity of the results to the present case study, the virtual comparison between the variables relevant to morphodynamics and the fluvial morphodynamics, the dependency between variables with regards to their effect in fluvial morphodynamics, and the possible overall relative importance of each variable to morphodynamics for different case studies.

The present study applied a stochastic method (MCS) using a numerical simulation software (HEC-RAS), to analyse the morphological response of fluvial morphodynamics to a set of different simulated combinations of the variables considered most relevant to the morphodynamical behaviour of a river. These variables were flow, granulometry and bed roughness, and their representative values taken on the analysis were, respectively, the mean flow value of each flow series, the D_{50} value of each granulometric profile and roughness original values. An independent and a joint sensitivity analysis were performed. The first one was performed on a first step to provide the insight of the relationship between each variable and the channel's morphodynamics, with regards to (1) the correspondent magnitude of each variable, in terms of morphological changes of the river bed, thereby observing their correspondent maximum range (taken from the entire channel's length), and (2) the natural/unnatural increasement or decreasement hierarchic order's value of each variable (which underlies a possible linearity/non-linearity) with respect to 4 aspects, namely, erosion, deposition, balance and total impact. The joint sensitivity analysis provides the insight of the complexity between the interdependencies between the variables and their overall importance to the morphological behaviour of a river bed, by means of holistic statistics, representing them qualitatively and quantitatively.

In an overall, the results obtained present in increasing order of importance (with regards to the channel's morphodynamics sensitivity) bed roughness, granulometry and flow. Bed roughness presented, by far, the lowest level of importance to the river bed's morphological changes, whilst the variables granulometry and flow, presented a high level of importance, even though not equal but not very far from each other. The importance of a variable, when defining a fluvial channel's morphodynamics, mustn't be measured solely based on the magnitude of its effect in the morphodynamics overall variability but also based on the predictability of its effects on morphodynamics (i.e., monotonicity/linearity) and its interdependency with other relevant variables. Its imperative that these variables' relationship with fluvial morphodynamics, and with each other, is understood in the context of the strong non-linearity, since non-linearity is a characteristic of all the morphodynamical processes. These complex characteristics of fluvial morphodynamics were handled by the analyse of several statistics which represent different aspects of the morphodynamical evolution of the channel.

From the independent sensitivity analysis was possible to see that flow presented the highest range value on the overall morphological changes of the river bed (measured across the entire channel), which was approximately 2 and 6 times the highest range values presented on granulometry and bed roughness, respectively. A strong non-linearity was observed between each of the 4 aspects (relevant to the morphological changes) and each of the variables granulometry and flow, whilst bed roughness presented an approximate linear effect with the morphological changes. This is maybe due to the fact that each of the bed roughness' parameters were one single value, whilst the parameters of granulometry and flow consisted in a set of values that were introduced on the simulation, thereby increasing the strong non-linearity.

The joint sensitivity analysis presented, in general terms, a high level of complexity in the interdependencies between the variables. In terms of variables' importance, flow had the highest importance level, followed by granulometry and bed roughness. The latter had a low impact on the morphological changes (regarding the analysed statistics), almost negligible.

These results can provide insight, regarding the comprehension and representation of the morphodynamics uncertainty effects, for future studies involving numerical simulation of morphodynamics processes, particularly relative to studies on sensitivity, reliability and risk, as it pertains to morphodynamically relevant variables. It is through studies such as this one that we can get a better understanding of the interaction of the different variables of uncertainty. The understanding of the relationship between morphodynamics, morphodynamically relevant variables and their respective sensitivities allows for a selection of the variables which require the most accurate definition, and consideration in numerical forecasting studies. At the same time, the quantification of morphodynamical sensitivities facilitates the understanding and representation of uncertainty in numerical studies into fluvial morphology.

Further validations of the present results are important in order to solidify these conclusions. These validations should consist in real field data.

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