"The Sensitivity Analysis of DEM Resolution and extent to Erosion and Sedimentation output using LAPSUS5 in the Sabinal Catchment (Spain) and Comparative Analysis Across Diverse Catchments"

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Abstract

The resolution of Digital Elevation Models (DEM) plays a crucial role in landscape evolution modelling, particularly concerning erosion and sedimentation processes. This study employs the LAPSUS5 model to investigate the impact of DEM resolutions and extent on erosion and sedimentation, focusing on six key parameters: erodibility, sedimentiability, annual rainfall, discharge exponent, slope exponent, and flow convergence factor. By conducting simulations with varying parameter values across different DEM resolutions and extent, including original and aggregated versions, the study explores the responses of the Sabinal catchment. While erosion responses generally show higher sensitivity in coarser resolutions, deposition behaviours are more variable, with unique responses for each parameter. In sequent Comparative catchment analysis with the same range of DEM resolutions to different extents reveals differing behaviours, although the outcome shows higher consistency but again suggesting that each DEM's response is unique, necessitating further studies to understand the specific relationships between DEM resolution and erosion/deposition processes for higher accuracy in Landscape evolution modelling.

Chapter 1

Introduction

In the realm of landscape modelling, a myriad of models has emerged over the years, each with its distinct focus and methodology, ranging from geomorphological to hydrological perspectives [1]. The complexity of landscape processes, coupled with their non-linearity and system heterogeneity, imposes significant limitations on modelling accuracy [2]. These limitations, often referred to as scale effects, underscore the criticality of spatial and temporal resolutions in determining model validity and efficacy [3, 4]. Central to dynamic landscape modelling are erosion and sedimentation processes, essential for understanding landscape evolution [5]. However, not all models consider these processes, and their relevance varies based on spatial and temporal resolutions. Considering the wide range of spatial and temporal scales involved in geomorphological processes, it is essential to employ a multi-scale modeling framework.

1.1. Motivation

Despite the importance of topographic attributes represented by Digital Elevation Models (DEMs) in geomorphological modelling, the systematic effects of DEM resolution on erosion and sedimentation processes remain largely unexplored. Therefore, this study aims to elucidate and quantify the impact of DEM resolution on erosion and sedimentation modelling, independent of landscape representations. Understanding the intricate interplay between DEM and model outcomes is essential for enhancing modelling accuracy and predictive capabilities. With tools like this, researchers can isolate elevation data as the variable of interest, allowing for a focused examination of how variations in DEM resolution or catchment measurement techniques impact model dynamics. By delving into the sensitivity of erosion sedimentation modelling to DEMs, this research aims to shed light on their profound influence on landscape evolution and modelling practices [6].

This study revolves around the exploration of the LAPSUS5 model, a multi-module dynamic landscape evolution model renowned for its versatility in simulating various processes such as overland erosion, land sliding, tillage erosion, and tectonics. Our research hones in on the influence of DEM resolution on erosion and sedimentation modelling within the framework of LAPSUS5 [7, 8]. At the heart of our investigation lies a deep-seated interest in unravelling the intricacies of DEM sensitivity and its impact on landscape evolution modelling, particularly within the domain of Landscape Evolution Models (LEMs) [9]. In LEMs, the gradient or elevation differences, DEM, emerge as a pivotal driving parameter [10]. These parameters play a crucial role in delineating terrain characteristics, whether it be through the tangent of the landscape's slope or the height difference integral to capacity-driven water-sediment models. Furthermore, the translation of height differences into erosivity underscores the fundamental role of DEM in shaping landscape dynamics. Utilizing a model such as LAPSUS5 affords us the unique opportunity to meticulously

manipulate elevation data while keeping all other variables constant. By selectively altering parameter such as DEM resolution, we aim to dissect the nuanced interplay between elevation data and landscape processes.

1.2. Outline of Thesis

The thesis unfolds with Chapter 2, which delves into the foundational concepts and existing literature pertinent to the study. Section 2.1 elucidates the underpinnings of geomorphology and landscape dynamics, exploring the intricate interplay between landforms, erosion processes, and sedimentation phenomena. Subsections 2.1.1 to 2.1.5 elucidate the significance of studying erosion and sedimentation processes, highlighting the pivotal role of DEM in capturing landscape intricacies and integrating them into LEM. The subsequent discussion in Section 2.2 outlines the scope and significance of the study, underscoring the imperative need to scrutinize the sensitivity of DEM and their resolutions within the context of dynamic landscape evolution. Section 2.3 succinctly delineates the research objectives, providing a roadmap for the ensuing chapters.

Chapter 3, Methodology, embarks on a detailed exploration of the research methodology employed. Beginning with Section 3.1, the selection of study areas is meticulously outlined, with a focal point on the Sabinal Catchment in Spain and additional catchments chosen for comparative analysis. Subsequent subsections delve into resolution variation, sources of DEMs, and the selection of appropriate models for analysis, providing a comprehensive overview of the research framework. Section 3.2 elucidates the model parameter, setting the stage for the ensuing sensitivity analysis.

Chapter 4, Sensitivity Analysis, forms the crux of the research endeavour. Section 4.1 delineates the experimental design, followed by a detailed exposition of the parameter sensitivity analysis methodology in Section 4.2. The graphical analysis and visualization techniques employed are expounded upon in Section 4.3, setting the stage for a comprehensive understanding of the results.

Chapter 5, encompasses the Discussion, offering insights into the limitations, data analysis, and results obtained. Section 5.1 delves into the total erosion and sedimentation analyses for the Sabinal Catchment, while subsequent sections unravel the findings of erosion and deposition analyses for comparative catchments and various DEM resolutions. Chapter 6, final chapter, concludes the outcome of this study with an outlook for future research directions and at the end meticulously curated list of references to anchor the study in existing scholarship.

Chapter 2

Back Ground and Literature Review

- ### 2.1. Foundations in Geomorphology, Erosion, and Digital Elevation Models

  - #### 2.1.1. Geomorphology and Landscape Dynamics

The field of geomorphology plays a pivotal role in understanding the variety, origins, and dynamic evolution of landforms on both Earth and other celestial bodies. Its core principles are built upon two critical elements: quantitative analysis of landscapes and the ongoing development of theoretical frameworks that explain the diverse processes shaping topography [11].

Geomorphology, as a scientific discipline, focuses on the examination of landforms, their origins, evolutionary trajectories, and the intricate mechanisms responsible for shaping them. This academic discipline integrated insights from several scientific domains, geological, hydrological,

climatological, and biological insights to unravel the intricate narrative embedded within the Earth's surface [12].

Geomorphological research centers around the exploration of the Earth's surface dynamic a perpetually evolving landscape influenced by a multiplicity of determinants. Geomorphologists scrutinize the intricate interplay of geological, climatic, tectonic, and anthropogenic influences that imprint their signatures on landscapes. These landscapes, ranging from grand mountain ranges to meandering river valleys, and arid deserts to fertile floodplains serve as historical records of environmental processes and their temporal progression [13].

The focus lies in scrutinizing the dynamics of landscapes This involves a meticulous examination of processes that drive the evolution of Earth's surface, including erosion, sedimentation, weathering, and tectonic forces. Geomorphologists unravel the intricate mechanisms governing the genesis of landforms, the meandering paths of rivers, the formation of hills, and the configuration of coastlines. Furthermore, this field delves into the interdependencies among these processes, and their sensitivity to changes in climate, vegetation, and human land use [14].

In the context of this thesis, we delve into the field of geomorphology with a particular focus on the sensitivity of modelling erosion and sedimentation processes to DEM and their spatial resolutions.

- **2.1.2. Significance of Studying Erosion and Sedimentation Processes**

The fields of geomorphology, hydrology, and sediment transport modeling play crucial roles in understanding how natural landscapes form and change over time. Among these processes, erosion and sediment redistribution are especially important because they shape the land both in the short

term and over many years. These dynamic processes are influenced by factors like the shape of the land, how water flows across it, and how it's used by people. To understand how landscapes have changed over time and predict how erosion might happen in the future, we need to bring together a lot of different kinds of data. This includes information about the shape of the land, what kinds of soil are present, and what kinds of plants grow there. By combining all of this data, we can get a clearer picture of how erosion works and how it might affect the land in the future [15].

Recognizing the importance of erosion and sedimentation processes is crucial for managing land and water resources effectively. Nowadays, there's a growing demand for precise mathematical models and formulas to estimate how much soil is being lost, how soil is moving around within landscapes, and how much sediment is being carried away by runoff water. These tools are essential for understanding the effects of different land management decisions, especially as land use becomes more intense. They help us understand how these practices might affect how productive the land is and the quality of the water. By using these models and formulas, we can get an idea of what steps might need to be taken to prevent or fix any problems that arise.[15].

However, the complexity of many natural terrains, both in two and three dimensions, challenges the predictability of existing models and empirical formulae. This complexity underscores the need for specialized investigations into the sensitivity of DEM to accurately model erosion and sedimentation processes. The significance of this research becomes even more pronounced when we consider the global scale consequences of accelerated soil erosion due to human-induced environmental alterations. Such alterations have led to increased geomorphic activity and sediment fluxes, resulting in environmental degradation and high economic costs. This, in turn, has sparked a growing demand for watershed- and regional-scale soil erosion models to delineate target zones where conservation measures are most likely to be effective [16].

Understanding erosion and sedimentation processes in natural landscapes is crucial. It not only enhances our understanding of geomorphic and hydrological dynamics but also plays a pivotal role in sustainable land and water resource management, environmental preservation, and policy development on local and national levels.

- **2.1.3. Role of DEMs**

Over the past few decades, there has been a remarkable surge in our capacity to measure topographical features and most information about the Earth's surface came from paper contour maps (Figure 1a). These maps, however, had many significant coverage gaps, and quantifying distinctions between landscapes was a laborious task, involving the extraction of parameter such as slope angles and drainage basin dimensions from printed topographic maps or field surveys [17].

Twenty years later, the situation has changed dramatically. DEMs now cover almost the entire land area between 60° north and south latitudes, with resolutions as fine as three arc seconds, or about 30 m. Some countries have even achieved finer resolutions. Additionally, a growing portion of Earth's surface has been mapped using laser imaging technology, offering resolutions as precise as one meter or finer, with remarkable accuracy (Figure 1b).

*Figure 1. Examples of topographic data, then and now. **(a)** Portion of a US Geological Survey 1:24 000 contour map for part of the West Bijou Creek drainage basin, Colorado (Strasburg SE quadrangle). **(b)** Shaded relief image of the same area generated from a 1 m resolution (horizontal) digital elevation model derived from Airborne Laser Swath Mapping data collected in April 2007 by the National Center for Airborne Laser Mapping (NCALM). Images are approximately 3 km wide; the north is up [1].*

2.1.4. Integration of LEM with DEM

Landscape Evolution Models (LEM) are mathematical theories that describe how various geomorphic processes interact to shape the Earth's surface over time. These models consider factors such as erosion, sediment transport, and tectonic activity to simulate the evolution of topography. By incorporating the fundamental physics and chemistry of geomorphic processes, landscape evolution models provide insights into how landforms change and develop. They are essential tools for studying long-term landscape dynamics, understanding the impact of environmental changes, and predicting future landform evolution.

LEMs serve a number of roles in science. First, they embody the community's latest ideas about how various physical and chemical surface processes interact to shape the Earth's surface and transfer crustal mass from one place to another. Second, they allow us to visualize and quantify

the consequences of various hypotheses about process dynamics. For many researchers, the ability to visualize animated scenarios of landscape evolution – even if they are purely hypothetical – provides a powerful stimulus to the imagination and enhances our ability to interpret the landscape. Likewise, numerical models make quantitative, testable predictions about landforms and their responses to various types of forces. By revealing the logical consequences of our hypotheses, they direct our attention to those features of the landscape that provide the clearest tests of these hypotheses [18].

One key parameter of LEM involves the utilization of DEM. These high-resolution representations of Earth's topography serve as foundational input for LEMs. DEMs not only provide an accurate depiction of the current terrain but also play a pivotal role in assessing how alterations in DEM resolution impact the modelling of erosion and sedimentation processes, which aligns with the central focus of this thesis [19].

Figure 2. Landscape evolution models, then and now. (A) Conceptual sketch of stages in landscape evolution according to the model of W.M. Davis, from the 4th edition of a popular geology textbook. (B) Three frames from a numerical model of landscape evolution, show the development of topography and fan–delta complexes in response to the vertical motion on a pair of normal-fault blocks. The block toward the bottom in the images is subsiding relative to base level along the lower edge, while the block in the background is rising. The shoreline position is shown by the heavy gray line. Lighter colours indicate higher altitudes, and vice versa [1].

At the same time, theories about landscape evolution have significantly advanced in detail and complexity. Not long ago, a 'landscape evolution model' was simply a descriptive story that explained how a landscape changed over geological time periods (Figure 2A). William Morris Davis's idea of the geographical cycle is a good example of this kind of model. However, by the late 20th century, the meaning of the 'landscape evolution model' changed. It started to refer to a mathematical model that explains how different geomorphic processes shape the landscape over time (Figure 2B). Typically, the equations that describe landscape evolution are very complex and can't be solved exactly. They require numerical methods to find solutions. As a result, the term 'model' now includes both the theoretical ideas and the computer programs used to calculate approximate solutions to these equations.

2.1.5. Relevance of DEM and their resolution in LEM

Topography is one of the soil-forming factors and, therefore, affects the soil characteristics that determine the use, management, conservation and degradation of this resource [20]. In the case of erosion, topography is a factor that influences the transport capacity or re-deposition potential of soil by water, depending on the particular characteristics of the landscape. This process has been related to variables such as slope length and steepness, curvature, shape and uniformity of the slope [21]. DEM is a source of data with a high potential to quantitatively characterize topography as an important input for different erosion models [22] [23]. Three-dimensional data for slope gradient, slope curvature and relative positions of points are determining factors in modelling erosion and water flow [24]. DEMs have become increasingly valuable as data sources for both visual and mathematical analyses of topography and landscapes, as well as for modelling landforms.

DEMs are one of the main inputs whitin LEM calculations. They play a critical role in helping us better understand how the Earth's surface changes over time. DEMs provide scientists with highly detailed maps of the land, which can be seamlessly integrated into LEMs. The level of detail, or resolution, in these DEMs, is one of the key parameters that greatly influences the accuracy and effectiveness of LEMs. Maps come in various sizes and levels of detail, often tied to specific geographic reference points within individual countries. This diversity leads to inconsistencies when we cross national borders. When it comes to DEM, the level of detail, or resolution, is a critical factor, especially in sensitivity analyses like the one conducted in this thesis. As a hypothesis, the choice of different DEM resolutions can have a impact on the accuracy of predictions related to erosion and sedimentation within LEM. Researchers can experiment with various DEM resolutions to better understand how changes in terrain detail influence the outcomes

of their models. This helps us appreciate the significance of resolution in landscape modelling [25].

- **2.2. Scope and Significance of the Study**

In the realm of landscape evolution modelling and erosion research, it is important to underscore the pivotal role of DEMs as a crucial input parameter. Much like rainfall and erodibility, DEM occupies a foundational position in the equation governing these intricate natural processes. However, their significance transcends even these fundamental elements, particularly within the domain of erosion modelling and landscape evolution.

The assumption of the DEM resolution impact on LEMs can highlight the importance of making thoughtful decisions about resolution when conducting landscape modelling research. These choices can have a profound influence on the results of the model and our comprehension of the processes that shape the Earth's surface. This assumption's heightened importance arises from the fact that one of the primary driving forces behind these dynamic phenomena is the gradient, often represented as dh, which signifies the difference in elevation between two distinct locations. This gradient, in essence, serves as the wellspring of energy and capacity, dictating the trajectory and magnitude of landscape transformation. Therefore, DEM, by providing an intricate portrayal of terrain elevation, emerges as an indispensable cornerstone in our relentless pursuit of comprehending the complex dynamics of erosion and landscape evolution. They facilitate precise calculations and simulations that shed light on the intricate interplay of geological and hydrological processes shaping the Earth's surface. Therefore, recognizing the critical importance of DEMs as essential input parameter is not only justified but also crucial for advancing our comprehension of these fundamental natural processes.

- **2.3. Objectives**

This study aims to carefully compare how LEM outputs react to different levels of DEM resolutions and extents. The main goal here is to figure out if there is a best level of resolution and extent, for Landscape Evolution Modelling or that resolution or extent does not matter. This knowledge will help us make these models more accurate and reliable in predicting landscape changes caused by erosion and sedimentation. Additionally, we're exploring how the sensitivity of these models changes with varying resolutions and extents. This will help researchers to evaluate the right resolution for specific research goals and places.

Overall, this research aims to help us better understand how landscapes evolve due to the spatial interaction of erosion and re-sedimentation processes. By studying how DEM resolutions and extent affect model results, we can gain a deeper understanding of these complex processes. This knowledge can be used in various ways, from conserving the environment to managing land and preparing for the impacts of geomorphic changes on nature.

Chapter 3

Methodology

- **3.1 Selection of Study Area**

In the pursuit of unravelling the complexities of landscape dynamics and erosion processes, selecting an ideal study area is paramount. Our choice of study area involves a meticulous consideration of various factors, including accessibility, data availability, and environmental significance. This section outlines why we selected the Sabinal Catchment in Spain for our research. By exploring its distinctive features and significance, we aim to explain why this area is well-suited for studying erosion and sedimentation processes.

Furthermore, while the Sabinal Catchment in Spain stands as a primary focus of our study, it's important to note that our research isn't confined to this single location. In addition to our detailed examination of Sabinal, we will expand our analysis to include a range of comparative catchments. These diverse catchment areas will provide valuable insights into the broader applicability of our findings and offer a comprehensive perspective on the dynamics of erosion and sedimentation processes across different landscapes, resolutions and extents.

- **3.1.1 Sabinal Catchment, Spain**

The catchment area of the Sabinal River, a tributary of the Guadalhorce River, is located just northwest of the town of Alora, Malaga province, Andalucia, southern Spain (Figure 3). The Sabinal River originates from a saddle area at around 300 m altitude and flows in between two larger hills (reaching 500 to 600 m altitude) down to its confluence with the main river around 140 m.

Figure 3. . Location of Sabinal catchment, Southeastern Spain

The Sabinal River basin is located between the coordinates $16°42'$ and $16°54'$ north between the latitude $93°20'$ and $9°02'$ west, with an elevation in the range of 384 to 1064 m above sea level and an average elevation of 724 m above sea level.

The Sabinal River is one of the watercourses within the catchment and flows into the Mediterranean Sea. The Sabinal catchment is characterized by a semi-arid to arid climate, with dry hot summers and mild wet winters. The region experiences low annual rainfall, averaging around 540 mm per year. The area is also prone to flash flooding due to the high-intensity rainfall events that occur during the wet season. The Sabinal catchment is predominantly used for agriculture, with the cultivation of citrus fruits, olives, and almonds being the primary crops. Land use within the catchment also includes natural vegetation, such as shrub land and forests.

Geologically speaking, the area has been studied as early as 1859 by Ansted who gave the first geological and geomorphological description of the region surrounding the, in those days, the small harbour city of Málaga. This research area, comprising the middle to lower Guadalhorce river basin, was chosen for its dynamic landscape of mountains and hills, a variety of different lithologies within a small area, its interesting complex geological history and active landscape processes ranging from tectonics, land use changes to land degradation. Furthermore, this area has been used for the past ten years by the Wageningen University field practical "Sustainable Land Use" integrating the disciplines of Agronomy, Irrigation, Soil and Water Conservation, Nature Conservation, GIS & Remote Sensing and Soil Science. Over the years this resulted in various publication about the research area of different disciplines.

- **3.1.2. Additional Catchments for Comparative Analysis**

Within the section, we introduce a group of catchments meticulously chosen to enhance our comprehensive comparative analysis of Landscape Evolution Models (Figure 4). These catchments possess unique geographic attributes, such as their extents, altitude ranges, average slopes, and the variation in slope across their landscapes (Table 1). It's crucial to emphasize that, in our investigation, we concentrate primarily on evaluating how our LEM responds to alterations in DEM resolution and extent. While these catchment characteristics offer valuable insights into diverse terrains, our primary objective remains to assess the sensitivity of our models to changes in DEM resolution and extent. Therefore, we exclusively manipulate the DEM input while keeping other catchment attributes constant as comparable to all settings of the Sabinal catchment. By doing so, we aim to delve into the sensitivity of differing only resolutions and extents on the outcomes of our models. The table and figures presented in this section succinctly encapsulate these vital catchment details pertinent to our comparative analysis, providing a clear foundation for our subsequent discussions and conclusions.

Figure 4. Sabinal and other comparative catchments location

Table 1. Characteristics of Selected Comparative Catchments

Catchments	Area (km2)	Range of altitude (m)	Mean slope (˚)	Standard Deviation of slope
Bravura (Portugal)	17.60	88.93 - 566.66	15.83	6.42
Prado (Spain)	55.05	434.83 - 1153.85	6.45	5.78
Guadalhorce (Spain)	3346.31	0.83 - 1817.65	11.49	9.61
Bergantes Up (Spain)	70.26	694.09 - 1276.99	14.10	7.38
Entire bergantes (Spain)	1201.34	444.00 – 1862.16	13.94	8.46

- **3.2. Resolution Variation**

In order to comprehensively investigate the influence of DEM resolution on erosion and sedimentation modelling, a systematic selection of resolution levels was undertaken. This section

delineates the chosen DEM resolutions for both the Sabinal Catchment and the comparative catchments, each serving specific research objectives.

- **3.2.1 Sabinal Catchment DEM**

In the Sabinal Catchment, a series of DEM were meticulously prepared to assess the impact of varying resolutions on modelling outcomes. The following DEM resolutions were selected:

- 5 m Resolution: This high-resolution DEM facilitates detailed topographic analysis within the Sabinal Catchment (Figure 5a).

- 10 m Resolution: A moderate-resolution DEM offering a balance between detail and computational efficiency (Figure 5b).

- 25 m Resolution: A coarser resolution, which serves as a benchmark for comparative analysis (Figure 5c).

- Aggregated 10 m Resolution: An aggregated DEM generated by combining cells from the 5 m resolution data, providing insights into the effects of aggregation on modelling results.

- Aggregated 25 m Resolution: A similarly aggregated DEM, synthesized from the 5 m resolution data, offering a coarse-grained perspective.

Figure 5. DEMs of the Sabinal catchment for 5 m (a), 10 m (b), and 25 m (c)

These diverse DEM resolutions were chosen within the Sabinal Catchment to assess differences in modelling outcomes, considering various levels of terrain detail and computational demands.

- **3.2.2 Comparative Catchments DEM**

In addition to the Sabinal Catchment, a comparative analysis was conducted across five other catchments (Figure 6-9). The comparative catchments were selected to closely match the 25 meter and aggregated 25 meter resolutions of the Sabinal Catchment and, thereby, enable a rigorous evaluation of DEM behavior (Table 2).

Table 2. DEM resolutions for comparative catchments

Catchment	Bravura	Prado	Guadalhorce	Bergantes Up	Entire Bergantes
DEM resolution	25 m	20 m	25 m	20 m	20 m

Figure 6. DEM of the Bravura Catchment with 25m resolution

Figure 8. DEM of the Prado Catchment with 20 m resolution

Figure 7. DEM of the Guadalhorce Catchment with 25 m resolution

Figure 9. DEM of the Bergantes up and Entire Bergantes Catchments with 20 m resolution

The specific objective behind including catchments with comparable resolutions was to discern patterns in erosion and sedimentation modelling outcomes. These catchments not only facilitate the assessment of the Sabinal Catchment's behaviour but also contribute to the broader understanding of DEM resolution effects across diverse geographic contexts.

The selection of these resolution levels, both within the Sabinal Catchment and across the comparative catchments, forms the foundation for a comprehensive sensitivity analysis, allowing for the systematic exploration of DEM resolution's impact on erosion and sedimentation modelling.

- **3.3. Digital Elevation Models Sources**

In our study, the DEM serve as the foundational datasets for conducting erosion and deposition modelling within the Sabinal Catchment. These DEM provide detailed representations of the catchment's topography and elevation, enabling accurate spatial analysis of geomorphic processes. Below, we provide a comprehensive list of the sources from which we obtained the DEM data, each contributing to different resolution levels within our research:

- **For 25 m Resolution (Military) DEM**

Source: Servicio Geográfico del Ejército, 1997.

Dataset: Cartografía Digital, MDT 25, uf23, uf24, uf33, uf34.

Institution: Servicio Geográfico del Ejército, Jefatura de Información Geográfica, Madrid.

The 25m resolution DEM data were acquired from Servicio Geográfico del Ejército and are sourced from their Cartografía Digital, MDT series. These datasets, specifically uf23, uf24, uf33, uf34, offer a valuable foundation for our research, particularly for assessing erosion and deposition dynamics at a coarser spatial scale.

- **For 10 m Resolution DEM**

Source: Junta de Andalucía, 2008.

Dataset: Modelo Digital del Terreno 2008-2009. 10 metros/píxel (MDT10_2008-09).

Institution: Servicio de Producción Cartográfica, Instituto de Estadística y Cartografía de Andalucía.

The 10m resolution DEM data were sourced from Junta de Andalucía's Modelo Digital del Terreno 2008-2009 dataset, specifically MDT10_2008-09. This dataset provides a higher level of spatial detail compared to the 25m resolution data and contributes to a more nuanced analysis of terrain characteristics within the Sabinal Catchment.

- **For 5 m Resolution DEM**

Source: 5 meter Digital Elevation Model, 2016.

Dataset: Modelo Digital del Terreno de Andalucía.

The 5m resolution DEM data were obtained from the Modelo Digital del Terreno de Andalucía dataset. Accessible through the online catalog of IdeAndalucía, this dataset offers a finer spatial resolution, which is instrumental in capturing detailed topographic variations within the study area.

- **For Derived 10 m and 25 m Sabinal DEM**

Method: ArcMap, Spatial Analyst, Aggregate Tool, 2 respective 5 cells, selecting the lowest on.

In addition to the above-mentioned DEM sources, we derived specific 10m and 25m resolution DEM for the Sabinal Catchment using GIS software (ArcMap) and the Spatial Analyst tools. By aggregating or resampling the existing DEM to achieve the desired resolutions, we ensured consistency in the data and tailored it to our research requirements.

These diverse sources of DEM data, ranging from coarser resolutions to finer details, form the basis of our analysis, allowing us to investigate the sensitivity of erosion and deposition modelling to DEM resolution within the Sabinal Catchment. This comprehensive dataset collection enables

a robust examination of terrain dynamics and landform changes, contributing to the depth and accuracy of our research findings.

- **3.4. LEM LAPSUS**

In the following sections, we delve deeper into the specifics of the LEM LAPSUS erosion-deposition modelling. However, before we explore the intricacies of the erosion deposition model, we should establish some fundamental concepts that form the foundation of our study. These basic principles will help us better grasp the mechanisms at play in our erosion and deposition modelling endeavours.

- **3.4.1. Model Selection**

In our quest to investigate erosion and sedimentation processes in various landscapes, we've chosen to employ the LAPSUS model. The subsequent sections will provide an in-depth exploration of this model and its key components, shedding light on how it facilitates our research into landscape evolution.

- **3.4.2 Basic concepts**

This study employs the LAPSUS (Landscape Process Modelling at Multi-Dimensions and Scales) approach, drawing inspiration from the early contributions of Kirkby [26] [27] [28], and Foster and Meyer [29] [30]. The fundamental premise of this approach lies in the recognition of potential energy within flowing water as the driving force responsible for the transport of sediment across the landscape [6]. An additional pivotal assumption involves the application of the continuity equation to elucidate sediment movement. This continuity equation posits that the disparity between sediment input and output reconciles with the net variation in sediment storage. Within a

quasi-steady state framework, Foster and Meyer [29] [30] articulated the continuity equation for sediment transport downslope as follows:

$$-\frac{\partial z}{\partial t} = \frac{C-S}{h}$$ (Equation. 1)

In this equation, "z" symbolizes elevation (measured in m), "t" denotes time (in seconds), "C' represents sediment transport capacity (measured in cubic m per second), and "S" represents the sediment transport rate (expressed in cubic m per second). The term "h" embodies different meanings depending on the prevailing conditions: during erosional phases, "h" characterizes detachment rate, while during sedimentation phases, it signifies the settlement rate. To ascertain changes in elevation "∂z" over a specified time increment "∂t", it is imperative to compute alterations in the sediment transport rate "∂S". These alterations in transport rate are intricately governed by the transport capacity "C" whereby an excess capacity leads to sediment detachment (e.g., erosion, where the surface is lower), whereas a deficit capacity diminishes the quantity of sediment in transit (e.g., sedimentation, where the surface is higher). According to Foster and Meyer, subsequent to integration and the assumption of constancy in transport capacity, detachment, or settlement capacity within a finite element, the rate of sediment in transport can be calculated as follows:

$$S = C + (S_0 - C)\, e^{-dx/h}$$ (Equation. 2)

This expression encapsulates the dynamics of sediment transport rate, where "S" signifies the rate of sediment transport (measured in cubic m per second) over a finite element length "dx" [28]. The calculation is contingent on the transport capacity "C" the initial sediment transport rate "S0",

and the characteristic "h" representing transport capacity relative to detachment capacity (C/D) or transport capacity relative to settlement capacity (C/T).

This fundamental framework forms the basis for comprehending sediment transport processes, enabling the exploration of erosion and sedimentation dynamics across landscapes.

To implement Equation 2 effectively, it is imperative to establish expressions for transport capacity "C" detachment capacity "D" and settlement capacity "T". In this study, these capacities are calculated as functions of discharge and slope, drawing on the works of Kirkby, Willgoose, and Montgomery and Foufoula-Georgiou [31-33]. These calculations are defined as follows:

> **Transport Capacity (C):** The transport capacity "C" is calculated as a function of discharge "Q" (in cubic m per unit time) and the slope tangent ($\partial z/\partial x$). Parameter "m" and "n" are constants, with the inclusion of a dummy variable to ensure proper unit correction.
>
> $$C = \alpha Q^m \Lambda^n \qquad \text{(Equation. 3)}$$
>
> **Detachment Capacity (D):** Detachment capacity "D" is determined as a function of discharge "Q" and slope tangent ($\partial z/\partial x$), "K_{es}" is an aggregated surface factor (1/m) assuming proportionality to a specific shear and a constant drag coefficient.
>
> $$D = K_{es} Q \, \Lambda \qquad \text{(Equation. 4)}$$
>
> **Settlement Capacity (T):** Settlement capacity 'T' is similarly expressed as a function of discharge "Q" and slope tangent ($\partial z/\partial x$), with "P_{es}" representing a factor indicating combined sedimentation characteristics (1/m).
>
> $$T = P_{es} Q \, \Lambda \qquad \text{(Equation. 5)}$$

It's essential to note that changes in sediment transport rates (S) and, consequently, in elevation (∂z) exhibit opposite directions under erosion conditions for "D" and sedimentation conditions for "T". This dichotomy is a crucial consideration when interpreting the modelling results within the study.

- ### 3.4.3. Model structure and flow routing

LAPSUS adopts a grid structure comprised of square cells, each of uniform size. These cells represent generalized segments of the landscape, encompassing various unique attributes, including altitude and soil composition. The model's architectural design strategically integrates both two-dimensional and three-dimensional elements into the temporal dimension. Consequently, the model evaluates capacity dynamics in a two-dimensional context, as it primarily accounts for gravitational force and downslope water flow within finite elements. Nevertheless, for the estimation and routing of incoming and outgoing water and sediment fluxes, the model extends its assessment to the surrounding grid cells across the entire three-dimensional landscape [34].

The finite element methodology entails variable lengths while maintaining a consistent unit width, albeit at varying resolutions for each element. To examine the routing of runoff, this study conducts a comparative analysis of two methods: steepest descent and multiple flow directions. These approaches yield estimates of discharge. Historically, the steepest descent method has been widely adopted in conventional hydrological and geomorphological models and GIS software packages [31, 35].

The alternative method of calculating multiple flow directions involves the distribution of flow from a given cell to all adjacent downslope neighbors. This distribution is governed by specific weighting factors assigned to each fraction [36]. The formulation of this process is expressed as:

$$f_i = \frac{(\Lambda)_i^p}{\sum_{j=1}^{\max 8}(\Lambda)_j^p} \qquad \text{(Equation. 6)}$$

In this equation, the fraction "f_i" signifies the proportion of flow exiting a cell in direction "i" It is determined by evaluating the difference in elevation or slope gradient (∂z) in direction "i" raised to the power factor *"p"* that is the flow convergence factor used in sensitivity analysis and subsequently dividing it by the summation of similar values for all neighbouring downslope cells (never exceeding eight), each raised to the power factor "p" [32].

This comprehensive approach to modelling structure and flow routing serves as a robust foundation for understanding and quantifying the complex interactions governing water and sediment movement across the studied landscape.

3.5. Model Parameter

The LAPSUS model as a LEM employed in this study relies on several critical parameter that govern erosion and sedimentation processes [6]. These parameters encapsulate various aspects of the natural landscape and influence the model's ability to simulate the dynamic behaviour of the Earth's surface. The study focuses on the following key parameter:

- Erodibility (K_{es}): This parameter represents the susceptibility of soil or sediment to erosion by erosive agents such as water or wind. It characterizes how easily soil particles detach and entrain into the flow.
- Sedimentibility (P_{es}): Sedimentiability relates to the settling rate of suspended sediment particles in a fluid medium. It defines how quickly sediment particles are deposited from the flow.

- Annual Rainfall (*prec*): Rainfall patterns play a crucial role in erosion and sedimentation processes. These parameters account for the amount and intensity of precipitation, which influence runoff and sediment transport.

- Discharge Exponent (m): The discharge exponent controls the relationship between discharge (flow rate) and sediment transport capacity. It determines how changes in discharge impact sediment transport.

- Slope Exponent (n): Slope exponent characterizes the influence of slope steepness on sediment transport. It describes how changes in slope affect sediment movement.

- Flow Convergence Factor (*p*): This parameter represents the convergence of water flow and sediment capacity in the landscape, influencing the accumulation or redistribution of water and sediments.

- **3.6. Sensitivity Analysis**

- **3.6.1. Experimental Design**

In our pursuit to comprehensively evaluate the sensitivity of the LEM and its responses to specific parameters, it is imperative to maintain a consistent foundation across all DEM. Thus, we have established a fundamental base scenario that remains unaltered throughout our experimentation with different DEM. The rationale behind this approach is to ensure that our sensitivity analysis occurs under absolute and uniform conditions.

By adhering to a single base scenario across all DEM, we intentionally avoid the process of calibration tailored to individual datasets. While calibration can be valuable in certain contexts, our objective is distinct. We aim to scrutinize the model's sensitivity to alterations in specific parameters, holding all other variables constant. This deliberate consistency allows us to draw

robust conclusions regarding parameter sensitivity, unaffected by variations introduced through model calibration.

This approach offers a clear advantage: it enables us to assess the impact of parameter modifications in a controlled and standardized environment. It facilitates a direct comparison of the model's responses to changes in erodibility, sedimentiability, rainfall, discharge and slope exponents, and the convergence factor across various DEM. As a result, we can discern patterns, trends, and variations in model outcomes that are solely attributable to the parameter under investigation, unclouded by differences in model calibration. By adopting this rigorous and uniform experimental setup, we bolster the reliability and validity of our sensitivity analysis. The insights gained from this approach will provide a nuanced understanding of how specific parameters influence landscape dynamics, thereby contributing significantly to our research objectives.

In the subsequent sections, we delve into the specifics of our parameter sensitivity analysis, elucidating the nuances of each parameter's impact on the model's behaviour across different DEM.

- **3.6.2. Parameter Sensitivity Analysis Methodology**

Our endeavour to scrutinize the LAPSUS Model's sensitivity to various parameter unfolds systematically and rigorously. To achieve this, we designed a structured sensitivity analysis, ensuring a meticulous examination of the model's responses to specific parametervariations. In the pursuit of this analysis, we adhered to a consistent approach across all DEM under investigation.

For each DEM considered, we meticulously crafted six distinct sets of data, each with a unique focus on one of the model's parameters. These parameters, namely erodibility (K_{es}),

sedimentiability (P_{es}), Annual rainfall *(prec)*, discharge exponent *(m)*, slope exponent *(n),* and convergence factor *(p),* were subjected to controlled modifications. The process commenced by establishing a baseline scenario with parameter values set at 100%. Subsequently, we initiated incremental changes, adjusting the parameter of interest in 2.5% increments. This iterative approach allowed us to systematically explore the model's responses to incremental parameter adjustments, providing a comprehensive spectrum of outcomes (Table 3).

Crucially, we repeated this meticulous procedure for every DEM, ensuring that each dataset within the same DEM adhered to the same consistent percentage changes. This methodical approach maintains a level playing field across all DEMs, enabling us to disentangle the effects of each parameter's variation while maintaining uniformity in our experimental setup. By adopting this rigorous methodology, we unveil a nuanced perspective of the LEM's sensitivity to each parameter. The systematic exploration of parameter variations across multiple DEMs equips us with a profound understanding of how specific parameter changes impact the model's behaviour. Consequently, this approach empowers us to discern patterns, trends, and variations in model outcomes, systematically contributing to our research objectives and enhancing the robustness of our findings.

Table 3. Input parameter for base scenario and the variation of them

Parameter	Base scenario	Unit	Range of variation (value)
Erodibility (K_{es})	1.243E-4	1/m	5.5E-5 to 1.92E-4
Sedimentiability (P_{es})	1.243E-4	1/m	5.5E-5 to 1.92E-4
Annual Rainfall *(prec)*	0.555	m	0.24 to 0.86
Discharge Exponent *(m)*	2	-	0.9 to 3.1
Slope Exponent *(n)*	2	-	0.9 to 3.1
Flow Convergence Factor (*p*)	4	-	1.8 to 6.2

The adjustments made to Equation 3 involve setting the *m* and *n* exponents to fixed values, as suggested by Kirkby (1987), under the assumption that only wash is the dominant process. Additionally, a uniform rainfall pattern is applied, characterized by both consistent amounts and intensity totalling 555 mm per year. To facilitate calculations in Equations 3 to 5, annual infiltration and evaporation are maintained at a constant rate of 63 percent, which is used to determine Q.

To ensure a comprehensive evaluation of parameter sensitivity, a consistent approach was adopted across all catchments considered in this study. The same base scenario, characterized by constant parameter values, was employed as a reference point for each catchment. In each catchment, the base scenario maintained identical parameter values, fostering a direct comparison of model behaviour and sensitivity. This consistency allowed for the assessment of how variations in resolution, rather than parameter values, influenced landscape dynamics.

In the case of the upper Bergantes catchment, a unique approach was adopted due to the availability of two distinct DEMs. One DEM represented the upstream Bergantes catchment itself, providing a localized view of landscape dynamics. Simultaneously, a broader-scale DEM covered a more extensive geographical area encompassing the entire Bergantes catchment including major tributaries. This dual DEM setup enabled the exploration of variations in landscape evolution behaviour within the sub-catchment and its surrounding context of the whole watershed.

The use of consistent parameter values across catchments with varying resolutions and the inclusion of dual DEM for the Bergantes catchment facilitated a comparative analysis. This analysis aimed to uncover any disparities or similarities in model responses, shedding light on the significance of DEM extent in landscape evolution modelling.

3.7. Graphical Analysis and visualization

In this study, sensitivity analysis was primarily conducted through data analysis and visualization techniques using Microsoft Excel. The approach employed graphical representations to assess the sensitivity of the LEM to variations in key parameter. Six critical parameter, including erodibility, sedimentiability, annual rainfall, discharge exponent, slope exponent, and convergence factor, were selected for sensitivity assessment. These parameters were systematically varied across a

range of values, ranging from 45% to 155% of their base values in 2.5% increments. This stepwise variation allowed for a comprehensive evaluation of parameter sensitivity.

Throughout the parameter sensitivity analysis, a key methodology was employed to enhance the comprehensibility of results. Both input and output changes were consistently expressed as percentages of the initial 100% input and output "standard" run. This approach was adopted to facilitate a more intuitive understanding of the variations and to enable direct comparisons between the diverse catchments and scenarios under investigation. By representing alterations in parameter values and resulting model outcomes in percentage terms, the study aimed to provide a clear and straightforward means of assessing the impacts of changing resolutions on the landscape evolution model. This systematic percentage-based presentation allowed for the identification of patterns, trends, and relative sensitivities across different catchments and resolutions, ultimately contributing to a more robust evaluation of the model's behaviour under varying conditions.

To evaluate the impact of parameter variations on model outcomes, sensitivity graphs and plots were generated for each parameter Digital Elevation Model (DEM) combination. These graphical representations illustrated how changes in parameter values influenced erosion and deposition dynamics within the LEM. The sensitivity analysis focused on interpreting trends observed in the graphical representations. Specific attention was given to identifying threshold values or critical points at which parameter variations significantly affected model behaviour. This process facilitated a nuanced understanding of how each parameter contributed to landscape evolution.

While more advanced statistical methods were not employed in this analysis, the simplicity and transparency of the graphical approach allowed for easy reproducibility. By providing a

straightforward visual representation of sensitivity trends, this methodology enhanced the accessibility of the findings to a broader audience.

Chapter 4

Data Analysis and Results

In this chapter, we embark on a comprehensive exploration of the data analysis and results derived from our study. The primary focus is on understanding the intricate dynamics of erosion and deposition within diverse catchments, as influenced by variations in key parameter and digital elevation model (DEM) resolutions and extents. We present a detailed analysis of total erosion and total deposition, unraveling the intricate interplay between landscape parameter, resolutions, and catchment characteristics. Our objective is to shed light on the sensitivity of LEM to parameter changes and resolutions, thus enhancing our comprehension of geomorphic processes.

Based on the previously described base scenario, where all parameters were held constant across different resolutions, we conducted an analysis to determine the total erosion and total sedimentation (Figure 10). This approach allowed for a consistent comparison and assessment of these two key metrics.

Figure 10.Cumulative erosion and deposition for each resolution with same base scenario

It is obvious that erosion at the 25 m resolution and the aggregated 25 m resolution is lower compared to other resolutions. In terms of deposition, the aggregated 10 m and aggregated 25 m resolutions exhibit higher deposition rates than their original counterparts, while the 5 m resolution demonstrates the lowest deposition.

- **4.1. Total Cumulative Erosion Analysis for Sabinal Catchment**

In this section, we dive into a thorough analysis of total erosion, a fundamental process that shapes our planet's surface over long periods. We've conducted a meticulous investigation into how various factors affect erosion, examining five different DEM and several comparative catchments.

Our goal is to understand how changes in specific parameter, like erodibility, sedimentiability, and others, impact the rate of erosion within the Sabinal catchment.

We take a close look at each parameter, one at a time, making precise adjustments to see how they influence erosion rates. This approach helps us uncover the unique roles played by these parameters in shaping erosion patterns within the landscape. But our analysis doesn't stop there; we extend our examination to other catchments to detect broader trends that might apply beyond Sabinal's boundaries. By comparing erosion rates across catchments and considering the effects of DEM resolution, we gain a more comprehensive understanding of how different factors and data quality interact to drive erosion processes.

- **4.1.1. Erodibility Parameter Analysis for Sabinal DEM**

In this section, we explore the sensitivity of the LAPSUS model to variations in the erodibility parameter across different resolutions of the Sabinal DEM whitin the same extent. The erodibility parameter was incrementally adjusted from 45% to 155% in steps of 2.5%. The resulting variations in erosion rates were calculated as percentages, providing insights into the model's sensitivity to changes in erodibility (Figure 11).

Across all resolutions, the LAPSUS model demonstrated a consistent and almost linear sensitivity to alterations in the erodibility parameter. This means that as the erodibility parameter increased or decreased within the specified range, erosion rates responded similar but not completely proportional. The sensitivity analysis allowed us to quantify this relationship.

For instance, at the 5 m resolution, erosion rates exhibited a percentage variation ranging from 45.1% to 154.6% (a 109.5% variation) in response to changes in the erodibility parameter. Similarly, other resolutions, including 10 m, 25 m, 10(5) m, and 25(5) m, displayed comparable linear sensitivities to the erodibility parameter. This consistent sensitivity pattern indicates that the

LAPSUS model responds predictably to variations in erodibility across a wide range of resolutions.

Such findings are invaluable for understanding how changes in erodibility can influence erosion.

Figure 11. Total Erosion output results for Erodibility parameter variation in the Sabinal catchment DEMs

- **4.1.2. Sedimentiability Parameter Analysis for Sabinal DEM**

Across all resolutions, the model's response to changes in the sedimentiability parameter was notably different from what we observed with erodibility (Figure 12). The graphs representing sedimentation rates remained almost flat, resembling horizontal lines. This means that, regardless of the resolution or variations in the sedimentiability parameter, the sedimentation rates showed minimal changes. Specifically, the percentage variation in sedimentation rates for all Sabinal DEM resolutions was negligible. These horizontal trends indicated that the LAPSUS model exhibited little sensitivity to alterations in the sedimentiability parameter or the erosion process. In fact, the

sedimentiability parameter expected not to influence erosion, therefore these small variations are remarkable and indicates that Indicate that spatially, the sedimentation capacity slightly alters some of the erosion capacities.

Understanding the model's response to variations in sedimentibility is crucial, as it highlights the specific parameter that exert a significant influence on the landscape evolution, while others may have a more limited impact.
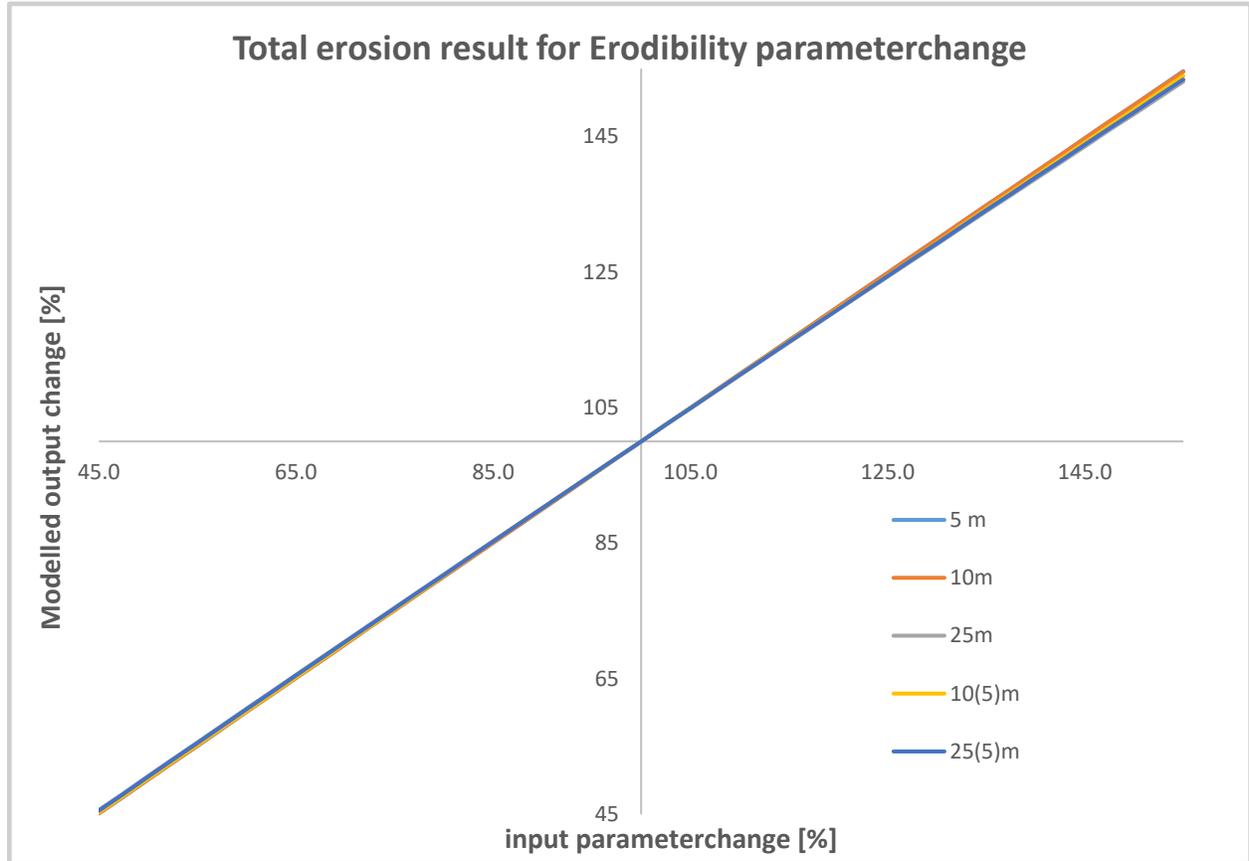

Figure 12. . Total Erosion output results for Sedimentiability parameter variation in the Sabinal catchment DEMs

- **4.1.3. Annual Rainfall Parameter Analysis for Sabinal DEM**

In this section, we shift our focus to the sensitivity analysis of the LAPSUS model concerning variations in the annual rainfall parameter for the Sabinal DEM, specifically for the erosion process.

Across all resolutions of the Sabinal DEM, we observed that the cumulative erosion total rates displayed a nearly linear relationship with changes in the annual rainfall parameter (Figure 13). In other words, as the annual rainfall parameter increased or decreased within the specified range, Total erosion rates showed a corresponding and nearly proportional change.

Analyzing the sensitivity further, we found that the extent of sensitivity varied slightly among the different DEM resolutions. Among the Sabinal DEM, the 25 m resolution exhibited the highest sensitivity to changes in the annual rainfall parameter. In contrast, the 10 m and aggregated 10 m from 5 m resolutions showed somewhat lower sensitivity. The aggregated 25 m resolution demonstrated a sensitivity level similar to that of the 25 m DEM. These findings suggest that, for the Sabinal catchment, the erosion process is relatively sensitive to variations in the annual rainfall parameter. Among the different DEM resolutions, the 25 m and aggregated 25 m resolutions appeared to be more responsive to changes in annual rainfall, whereas the 10m and aggregated 10 m resolutions exhibited a slightly lower degree of sensitivity. Nonetheless, all resolutions displayed a proportional sensitivity in erosion rates with respect to alterations in the annual rainfall parameter.

Figure 13. Total Erosion output results for Annual Rainfall parameter variation in the Sabinal catchment DEMs

- ### 4.1.4. Discharge Exponent Parameter Analysis for Sabinal DEM

In the analysis of the discharge exponent (*m*) parameter for cumulative erosion outputs, we observed some interesting trends. Before reaching the base scenario, where the discharge is less than 2, each DEM exhibited a unique behavior as a high sensitivity, with all of them showing an increase in erosion as discharge exponent increased, although at varying rates. Specifically, the 5 m DEM appeared to be the least sensitive to changes in discharge, displaying relatively minimal alterations (Figure 14). On the other hand, the 10m and 25 m DEM showed slightly more responsiveness but still less than their aggregated counterparts. Importantly, prior to the base

scenario, the changes ranged from 22% to 48%, indicating a more pronounced sensitivity across the resolutions during this phase.

However, the behaviour shifted significantly after reaching the base scenario, where the discharge exceeded 2. Interestingly, after the base scenario, we observed a marked reduction in sensitivity, with changes now ranging from 0.3% to 1.13%. This transition highlighted that coarser resolutions tend to be less sensitive to changes in the discharge exponent parameter after the base scenario, showing minimal variations in erosion outputs.

In summary, the 5 m resolution DEM exhibited lower sensitivity to discharge changes before the base scenario, while coarser resolutions, including 10m and 25 m, displayed greater sensitivity

Figure 14. Total Erosion results for Discharge exponent parameter variation in the Sabinal catchment DEMs

during this phase. However, after the base scenario, the sensitivity decreased significantly across all resolutions, with the coarser resolutions exhibiting almost no changes in erosion outputs.

- **4.1.5. Slope Exponent Parameter Analysis for Sabinal DEM**

For the Slope Exponent Parameter Analysis, it's notable that as the slope factor increases, erosion tends to decrease across all the DEM. The base scenario, where n=2, represents a critical point, as altering this parameter has varying effects. When we increase n, the impact on erosion is more pronounced than when we decrease it. The degree of sensitivity varies between the different DEM resolutions, with distinct patterns observed (Figure 15).

Starting with the 5 m resolution, the erosion output ranges from 100.45% to 97.23% as the slope factor increases, indicating a decrease in erosion, with a difference of -3.22%. Similarly, the 10m resolution exhibits a decrease in erosion from 100.57% to 96.05%, a difference of -4.52%, when n increases. In contrast, the coarser resolutions show a more significant effect. The 25 m resolution experiences a substantial reduction in erosion, shifting from 102.40% to 90.29%, marking a difference of -12.11%. Meanwhile, the 10(5) m resolution demonstrates a noticeable decrease from 101.14% to 94.71%, resulting in a difference of -6.43%. The 25(5) m resolution exhibits the most substantial sensitivity, with erosion plummeting from 102.09% to 88.63%, a difference of -13.46%.

Overall, the sensitivity to the slope exponent parameter is more prominent in coarser resolutions compared to finer ones. The aggregated DEM show heightened sensitivity in comparison to the original ones. In terms of sensitivity order, it follows the sequence: 25(5), 25, 10(5), 10, and 5. Additionally, it's worth noting that the 10m and aggregated 10m resolutions do not exhibit a consistent pattern of decrease but rather show variations, including both decreases and increases

in erosion. These results underscore the intricate relationship between slope exponent and erosion across different DEM resolutions, shedding light on the sensitivity and variability associated with this parameter in landscape modelling.

Figure 15. Total Erosion results for Slope exponent parameter variation in the Sabinal catchment DEMs

- **4.1.6. Convergence Factor Parameter Analysis for Sabinal DEM**

The analysis of the Convergence Factor Parameter reveals that, in general, total cumulative erosion output does not exhibit significant sensitivity to this factor (Figure 16). However, an intriguing observation emerges in the 5m DEM where a distinctive behaviour is noted. Unlike the other DEM, the 5m resolution experiences a slight decrease in the initial part of the graph followed by an increase in the latter part. It's worth noting that this change, although perceptible, remains relatively small, with fluctuations of less than 0.5%.

This dynamic reflects a net difference of -0.38% during the initial phase and a subsequent difference of 0.10% in the later phase. Contrasting this, the 10m resolution exhibits a slight increase in erosion, with values transitioning from 99.81% to 100.08%, reflecting a difference of 0.27%. Meanwhile, the 25 m resolution demonstrates a more substantial increase in erosion, progressing from 98.86% to 100.52%, marking a considerable difference of 1.66%. The aggregated 10 m resolution reveals a minor increase, shifting from 99.91% to 100.02%, resulting in a difference of 0.11%. In comparison, the aggregated 25 m resolution displays a notable increase, with values ascending from 99.01% to 100.47%, culminating in a substantial difference of 1.46%.

Figure 16. Total Erosion results for convergence factor parameter variation in the Sabinal catchment DEMs

In the broader context, coarser resolutions exhibit a slightly higher level of sensitivity compared to finer resolutions, highlighting the nuanced relationship between the flow Convergence Factor and erosion within different DEM resolutions. Furthermore, it's noteworthy that the original DEM shows greater sensitivity to this parameter than the aggregated ones.

4.2. Total Cumulative Sedimentation Analysis for Sabinal Catchment DEM

we delve into the comprehensive analysis of sedimentation outputs. This examination encompasses all pertinent parameters across the five DEM resolutions. The primary objective is to discern the sensitivity of sedimentation processes within Sabinal Catchment to variations in these parameters. By scrutinizing the intricate interplay between DEM resolution and sedimentation characteristics, we aim to shed light on the nuanced relationships that exist within this dynamic landscape modelling framework. This investigation will provide a comprehensive understanding of how Sabinal Catchment responds to different parameter alterations in sedimentation modelling.

- **4.2.1. Erodibility to total cumulative sedimentation**

The analysis of the Erodibility Parameter change concerning sedimentation outputs reveals a consistent pattern across all DEM resolutions (Figure 17). As mentioned above sedimentiability parameter not expected to influence erosion output but erodibility can have influence on deposition since the deposition is an indirect process and depends on erosion result. Changing erodibility exhibits a linear relationship with sedimentation, displaying nearly uniform behaviour regardless of the specific DEM resolution. This analysis underscores that all DEM resolutions exhibit strikingly similar responses to variations in the erodibility factor, with changes in sedimentation outputs remaining consistent. The differences in sedimentation outputs across different DEM are

minimal, amounting to less than a 5% variation. Nonetheless, the sedimentation results are notably sensitive to changes in the erodibility parameter, highlighting the importance of erodibility in shaping sedimentation processes within Sabinal Catchment.

Figure 17 .Total cumulative sedimentation results for Erodibility parameter variation in the Sabinal catchment DEMs

- **4.2.2. Sedimentiability to total cumulative sedimentation**

The analysis of the Sedimentiability Parameter total cumulative sedimentation outputs unveils that all DEM exhibit increasing behavior, albeit with differing slopes. Among the DEM resolutions, the 10 m resolution stands out with the steepest slope, indicating a nearly linear relationship between sedimentation and changes in the sedimentiability factor. Unlike previous analyses, here,

we cannot conclusively categorize finer or coarser resolutions as more or less sensitive, as the order of sensitivity is as follows: 10 m, aggregated 10 m, 5 m, aggregated 25 m, and 25 m (Figure 18).

To elaborate further, the 10m resolution and the aggregated 10m exhibit the highest sensitivity to changes in the sedimentiability parameter, making them the most responsive to variations. The 5 m resolution is found to be less sensitive than 10 m, 10(5) m, and 25(5) m, while the 25 m resolution, marked by the less steep slope in the graph, emerges as the least sensitive DEM among the others. This comprehensive sensitivity analysis highlights that sedimentation outputs are influenced by the sedimentiability parameter, with different DEM resolutions exhibiting varying levels of sensitivity. The insights provided here contribute to a nuanced understanding of the interaction between sedimentiability and sedimentation within the Sabinal Catchment.

Figure 18. . Total Deposition results for Sedimentibility parameter rvariation in the Sabinal catchment DEMs

- ### 4.2.3. Annual Rainfall to total cumulative sedimentation

In the analysis of sensitivity of the Annual Rainfall to total cumulative sedimentation outputs, the graph patterns consistently reveal an increasing trend for all DEMs, each characterized by a distinct slope. Notably, the 10m resolution demonstrates the lowest sensitivity to changes in rainfall, exhibiting a mere 7% variation. In contrast, the 25 m resolution is identified as the most sensitive to fluctuations in annual rainfall, presenting a substantial 104.6% variation. Furthermore, the 5 m and 10(5) m resolutions display remarkably similar behavior in response to changes in rainfall

(Figure 19). This sensitivity analysis underscores the influence of annual rainfall on sedimentation within the Sabinal Catchment. While all DEMs demonstrate an overall sensitivity to this parameter, their responsiveness varies, highlighting the intricate interplay between annual rainfall and sedimentation across different DEM resolutions.

The fact that increasing rainfall lead to higher discharge and it means more capacity for erosion and following re-sedimentation. It is worth noting that, based on the analysis of the Annual Rainfall Parameter for sedimentation outputs, it is not feasible to unequivocally determine whether finer or coarser DEM resolutions exhibit greater sensitivity to changes in annual rainfall. Instead, the sensitivity patterns appear to be more complex, with the 10m resolution displaying the least sensitivity and the 25m resolution showcasing the most significant sensitivity. The 5 m and 10(5) m resolutions, while distinct in their responsiveness, exhibit notably similar behavior. This intricate relationship between DEM resolution and sensitivity underscores the intricate dynamics governing the impact of annual rainfall on sedimentation within the Sabinal Catchment. These findings contribute to a more comprehensive understanding of the multifaceted interplay between annual rainfall and sedimentation, offering valuable insights for landscape modelling.

Figure 19. Total Deposition results for Annual Rainfall parameter variation in the Sabinal catchment DEMs

● **4.2.4. Discharge Exponent to total cumulative sedimentation**

The analysis of the Discharge Exponent Parameter to total cumulative sedimentation outputs reveals an intriguing and somewhat perplexing pattern across the various DEM resolutions. Each DEM exhibits its unique behavior in response to changes in the discharge exponent, making it challenging to discern a consistent sensitivity pattern (Figure 20). Obviously the lower exponent for discharge means higher influence of slope therefore it can effect erosion in first step and cause to re-sedimentation.

In the case of the 5m resolution DEM, sedimentation displays a gradual increase throughout the graph, with a range of variation spanning from 55.3% to 135.2%. This nearly linear relationship with the discharge exponent suggests that the 5 m DEM is comparatively less sensitive to this parameter than other resolutions. Conversely, the 25 m resolution DEM showcases an initial decrease, followed by a slight increase leading up to the base scenario. Beyond this point, it reverts to a decreasing trend. For the aggregated 25 m resolution DEM, the behavior differs significantly from the 25 m DEM. Here, sedimentation initially increases, then sharply decreases, ultimately reaching a point where sedimentation becomes almost negligible. The aggregated 10(5) m DEM exhibits a pattern that closely resembles the aggregated 25 m resolution, particularly in the post-base scenario phase. However, notable differences are observed in the initial part of the graph, marked by a more pronounced increase and a more substantial range of variation. The 10m resolution DEM stands out with the most distinctive variation. The range of variation prior to the base scenario can be as extensive as 2220%, only to stabilize and align with the aggregated 25 m and aggregated 10 m resolutions after reaching the base scenario.

These observations underscore the considerable variability in the response of sedimentation to changes in the discharge exponent, making it challenging to generalize sensitivity patterns. Each DEM resolution exhibits its unique trajectory, revealing the complex interplay between discharge exponent and sedimentation dynamics within the Sabinal Catchment.

Figure 20. Total cumulative sedimentation results in Discharge exponent parameter variation in the Sabinal catchment DEMs

● **4.2.5. Slope Exponent to total cumulative sedimentation**

The analysis of the Slope Exponent Parameter's impact on sedimentation outputs, as derived from the LAPSUS model, unveils intriguing patterns within the Sabinal Catchment across various DEM resolutions. Initially, all DEM exhibit a uniform response between 45% and 80% of the base scenario, indicating a relative in this range (Figure 21). However, beyond 80%, a distinct shift

occurs, leading to an increasing trend up to the base scenario (100%). Notably, after the base scenario, the sensitivity varies among resolutions. Post-base scenario, the 10 m resolution displays considerable sensitivity, with a pronounced impact on sedimentation. Following closely, the 5m resolution demonstrates high sensitivity, suggesting a notable response to slope exponent variations. Conversely, the aggregated 10 m and aggregated 25 m resolutions exhibit a less pronounced sensitivity, with fluctuations in the latter part of the variation range. The original 25 m resolution emerges as the least sensitive, displaying a more stable response.

An intriguing observation surfaces beyond 120% change from the base scenario, where DEM responses become increasingly unpredictable. Some resolutions, akin to the 10 m DEM, exhibit substantial increases, while others, like the 5m and 25 m resolutions, display fluctuations. In contrast, the aggregated 25 m and aggregated 10 m resolutions showcase decreasing behaviors. The diverse responses underscore the importance of carefully considering resolution-specific sensitivities in slope exponent parameter for accurate sedimentation predictions within the Sabinal Catchment.

Figure 21. . Total Deposition results for Slope exponent parameter variation in the Sabinal catchment DEMs

- **4.2.6. Convergence Factor to total cumulative sedimentation**

The exploration of the Convergence Factor Parameter's impact on sedimentation outcomes in the Sabinal Catchment reveals diverse sensitivities across different DEM resolutions. Notably, the 5m resolution DEM exhibits heightened sensitivity, displaying a clear reduction in sedimentation as the convergence factor varies. This heightened sensitivity reflects the model's ability to capture intricate details present in the finer 5m resolution. Similarly, the 10m resolution DEM shows

sensitivity, albeit slightly less pronounced than the 5m resolution. The consistent diminishing of sedimentation reinforces the nuanced influence of the convergence factor, even at a coarser scale. The aggregated 10m resolution maintains comparable sensitivity, indicating that the aggregation process doesn't eliminate the impact of convergence factor variations (Figure 22).

In the case of the 25 m resolution DEM, there is noticeable sensitivity, though less than in finer resolutions. The persistent decreasing behaviour underscores how coarser resolutions influence sedimentation dynamics. Finally, the aggregated 25 m resolution DEM exhibits minimal sensitivity, with sedimentation outputs remaining relatively stable despite changes in the convergence factor. This detailed analysis emphasizes the intricate interplay between DEM resolution and sensitivity to the convergence factor parameter in sedimentation modelling.

Figure 22. Total Deposition results for Convergence factor parameter variation in the Sabinal catchment DEMs

- **4.3. Sensitivity Analysis for Comparative Catchments and Sabinal Catchment**

In this section, we embark on a comprehensive examination of erosion dynamics, delving into the comparative analysis of the LAPSUS model outputs across multiple catchments, including larger extents. Our focus extends beyond the confines of the Sabinal Catchment, encompassing larger extents, catchment shapes and diverse geographic regions, each characterized by unique topography and environmental nuances. Given that we are using comparative catchments with varying extents and slopes, it is important to compare cumulative erosion and deposition against these factors. Analyzing how erosion and deposition correlate with catchment extent and slope will provide deeper insights into the influence of these variables on sediment dynamics within different catchments (Figure 23-24).

Figure 23. Erosion and Deposition outputs with Extent of comparative catchments

Figure 24. . Erosion and Deposition outputs with a mean slope of comparative catchments

It is evident that erosion, as a direct process, increases with larger catchment extents. However, this pattern does not hold for deposition, which does not show a consistent relationship with catchment extent. Additionally, when examining the mean slope of the comparative catchments and the cumulative erosion and deposition per ton, no clear pattern emerges. This indicates that other factors may be influencing the sediment dynamics beyond just extent and slope.

The key contenders in this comparative study include the 25 m resolution DEM from the Sabinal Catchment and its aggregated 25 m counterpart, in addition to catchments such as Bravura (with a 25 m resolution), Prado (20 m resolution), Guadalhorce (25 m resolution), Bergantes (20 m resolution), and the entire Bergantes watershed area (20m resolution). Our objective is to unravel

the nuanced responses of erosion processes to variations in key parameter across these diverse catchments. For each DEM, we meticulously explore alterations in erodibility, sedimentibility, annual rainfall, discharge exponent, slope exponent, and convergence factor. This comparative analysis brings to light the intricacies of landscape response to the Lapsus model, providing valuable insights for understanding erosion phenomena within varied geographical contexts.

- **4.3.1. Sensitivity and Erodibility Parameter Analysis**

In scrutinizing the erodibility parameter's impact on erosion outcomes across diverse catchments, we discern a consistent rising trend in almost all cases, marked by a nearly linear trajectory (Figure 25). Notably, the DEM from Bravura, Prado, Guadalhorce, Bergantes, and Sabinal, each with resolutions ranging from 20 m to 25 m, exhibit a collective sensitivity to variations in erodibility. The slopes of the trend lines for these catchments, indicative of the rate of change in erosion concerning the erodibility parameter, remain in similar pattern but the larger extent such as Entire Bergantes and Guadalhorce have lower sensitivityy, implying a shared responsiveness to this parameter alteration.

Interestingly, a nuanced distinction emerges in the behavior of Bergantes up and the entire Bergantes region, despite their identical 20 m resolutions. While maintaining a rising trend akin to the others, these catchments showcase a slightly divergent response, suggesting subtle variations in their erosion dynamics. This observation underscores the importance of considering catchment-specific characteristics beyond resolution, shedding light on the nuanced interplay of environmental factors. Furthermore, when assessing the Sabinal Catchment with both 25m resolution and its aggregated counterpart, a comparable rising behavior prevails. The slopes of their trend lines align closely, emphasizing the minimal influence of resolution alteration within the Sabinal region on erodibility sensitivity.

In summary, the erodibility parameter's influence on erosion, as revealed by the LAPSUS model, exhibits a consistent rising pattern across various catchments. While catchments with similar resolutions demonstrate similar sensitivities, the nuanced behaviors observed in specific regions and by considering extent of a catchments we can see that smaller catchments shows higher sensitivity than larger ones.

Figure 25. Total Erosion results for Erodibiality parameter variation in all comparative catchments DEM

- **4.3.2. Sedimentiability Parameter Analysis**

In delving into the intricacies of sedimentiabiality parameter analysis across diverse catchments, a remarkable consistency emerges in the LAPSUS model's response. Regardless of the distinctive characteristics of Bravura, Prado, Guadalhorce, Bergantes up, Sabinal, and the aggregated Sabinal catchment, all with resolutions ranging from 20 m to 25 m, the sedimentiabiality factor proves to be remarkably non-sensitive (Figure 26). Graphically represented by horizontal lines, these catchments exhibit minimal variation in erosion concerning alterations in sedimentiabiality. Notably, the catchments, including Bravura, Prado, and Guadalhorce, present near-flat trends with slopes approximating zero, indicative of the negligible impact of sedimentiability parameter variations on erosion outcomes. Moreover, the Sabinal Catchment, both with 25 m resolution and its aggregated counterpart, mirrors this non-sensitive behaviour, reinforcing the overarching pattern observed across distinct regions. A nuanced observation surfaces when considering Bergantes up and the entire Bergantes region. Despite maintaining non variation in trend, the slope of the trend line is insignificantly small decreasing, amounting to -0.002. This minute alteration underscores the practically non-existent sensitivity of these catchments to changes in the sedimentiability parameter.

In essence, the sedimentiability parameter analysis reveals a consistent theme of minimal sensitivity across various catchments, emphasizing the limited influence of this parameter on erosion outcomes. This uniform behaviour, characterized by nearly horizontal trend lines, signifies the resilience of the LAPSUS model to sedimentiability variations across diverse geographic settings.

Figure 26. . Total Erosion results for Sedimentiability parameter variation in all comparative catchments DEM

- **4.3.3. Sensitivity to Annual Rainfall change**

Embarking on an examination of the LAPSUS model's response to variations in the annual rainfall across diverse catchments offers intriguing insights. The range of variation in erosion outcomes, observed for Bravura, Prado, Guadalhorce, Bergantes up, Sabinal, and the aggregated Sabinal catchment, unveils a commonality in their increasing behavior (Figure 27). With resolutions

spanning from 20 m to 25 m, these catchments exhibit a linear trend, showcasing a propensity for heightened erosion with incremental adjustments in annual rainfall. Delving into the nuanced distinctions among these catchments, it becomes apparent that each follows a similar trajectory, albeit with slight differentials in their trend lines. Remarkably, the Entire Bergantes region emerges as less responsive to alterations in the annual rainfall parameter, showcasing a trend line with a more gradual slope. In contrast, Guadalhorce exhibits a slightly steeper trend, indicating a marginally higher sensitivity to changes in annual rainfall. Notably, all other catchments demonstrate heightened sensitivity, maintaining a consistent range.

Intriguingly, the 25 m resolution and the aggregated 25 m resolution from the Sabinal catchment showcase a striking similarity in their sensitivity to the annual rainfall parameter. The congruence in their trends suggests a harmonized response, reinforcing the robustness of the LAPSUS model across varying resolutions. In essence, the annual rainfall parameter analysis underscores a collective inclination towards increased erosion across catchments, portraying a consistent linear pattern despite minor divergences in trend lines.

Figure 27. Total Erosion results for Annual Rainfall parameter variation in all comparative catchments DEM

- **4.3.4. Sensitivity to Discharge Exponent**

The Discharge Exponent Parameter Analysis unveils distinctive behaviors among catchment DEM when subjected to alterations in the discharge exponent parameter (Figure 28). Notably, the behavior before and after the base scenario diverges significantly. Before reaching the base scenario, all catchments exhibit an increasing trend, albeit with varying ranges. Particularly, Bravura, Prado, Aggregated Sabinal, Sabinal, Guadalhorce, Bergantes UP, and Entire Bergantes showcase differing degrees of sensitivity, with Bravura being the most sensitive and Entire Bergantes the least. In contrast, after the base scenario, a discernible decline in sensitivity is

observed for all catchments, except for Entire Bergantes and Guadalhorce. These two catchments demonstrate a modest sensitivity, measuring less than 5%. The remaining catchments portray minimal sensitivity after the base scenario point.

This nuanced behaviour emphasizes the intricate relationship between discharge exponent variations and erosion outcomes in different catchments. The variability in sensitivity levels highlights the importance of considering both pre and post-base scenario phases in assessing the impact of discharge exponent parameter changes.

Figure 28. Total Erosion results for Discharge exponent parameter variation in all comparative catchments DEM

- **4.3.5. Sensitivity to Slope Exponent**

The Slope Exponent Parameter analysis sheds light on the diverse sensitivities exhibited by catchment DEM when subjected to variations in the slope exponent parameter. Distinctive patterns emerge both before and after the base scenario, providing insights into the nuanced relationship between slope exponent adjustments and erosion outcomes (Figure 29).

Before reaching the base scenario, the Entire Bergantes region stands out as the most sensitive, displaying a pronounced responsiveness to slope exponent changes. Guadalhorce follows, demonstrating a notable sensitivity, while the remaining catchments exhibit comparatively negligible sensitivities. This pre-base scenario phase underscores the varying degrees to which catchment DEM respond to alterations in the slope exponent parameter.

Conversely, after the base scenario, a convergence in sensitivities is observed among catchments. Guadalhorce, Bergantes up, and Entire Bergantes showcase minimal and almost negligible sensitivity, highlighting a stabilization in erosion outcomes. In contrast, Sabinal's original and aggregated DEM exhibit intermediate sensitivities, while Prado and Bravura retain the highest sensitivity levels post-base scenario. This comprehensive analysis illuminates the intricate dynamics between slope exponent adjustments and erosion outcomes, emphasizing the temporal dimension in understanding catchment-specific responses to parameter variations.
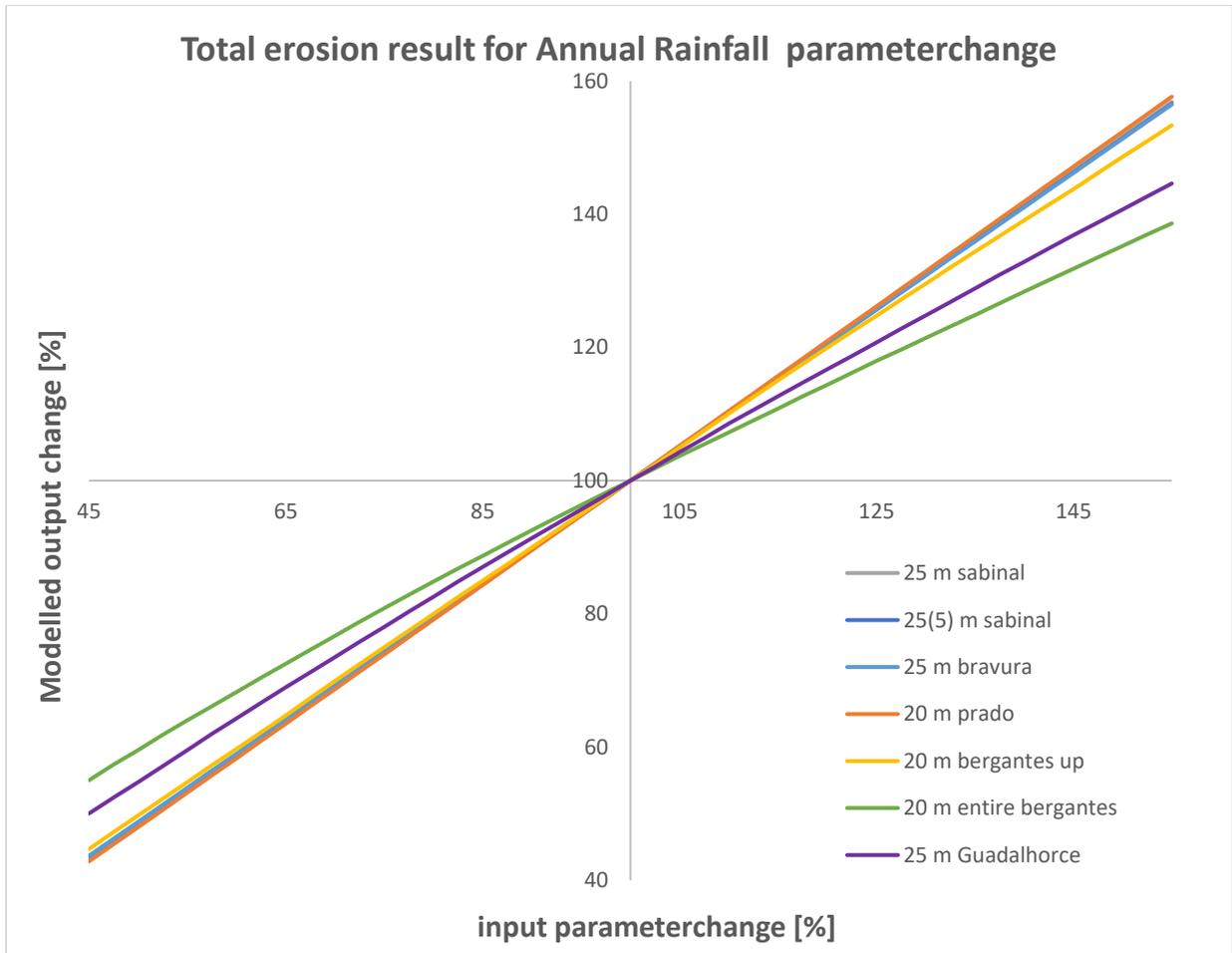
Total erosion result for Slope Exponent parameterchange

Figure 29. Total Erosion results for Slope exponent parameter variation in all comparative catchments DEM

- **4.3.6. Sensitivity to Convergence Factor**

The Convergence Factor Parameter analysis provides valuable insights into the impact of parameter variations on erosion outcomes across different catchment DEM. Notably, the range of variation for this parameter remains consistently minimal, falling below 5% for all catchments. This negligible fluctuation suggests a lack of sensitivity in erosion results to changes in the convergence factor parameter (Figure 30). In essence, the Convergence Factor Parameter appears to exert limited influence on the erosion dynamics of the studied catchments. The near-uniformity

in the negligible range of variation across all catchments implies a robustness or insensitivity of erosion outcomes to alterations in the convergence factor parameter.

Figure 30. Total Erosion results for Convergence factor parameter variation in all comparative catchments DEM

- **4.4. Total cumulative Deposition Analysis for Comparative Catchments and Sabinal Catchment**

In this section, we delve into a comprehensive analysis of total cumulative deposition output from the LAPSUS model, focusing on comparative catchments and the Sabinal catchment. Our aim is

to scrutinize and draw comparisons between these results and those obtained from various other catchments, each characterized by distinct resolutions and geographical features. The catchments under consideration include Bravura with a 25 m resolution, Prado with a 20 m resolution, Guadalhorce with a 25 m resolution, Bergantes up with a 20 m resolution, and the entire Bergantes region with a 20 m resolution. By examining the variations in key parameter, we seek to discern patterns and sensitivities unique to each catchment's sedimentation dynamics. This comparative approach allows for a nuanced exploration of how variations in terrain and resolution contribute to divergent sedimentation outcomes.

Throughout the ensuing sections, we will delve into the intricate details of parameter variations for each catchment, shedding light on the nuanced interplay between model parameter and sedimentation processes. Through this analysis, we aim to contribute valuable insights to the broader understanding of sedimentation dynamics in diverse catchment environments, elucidating the role of extent and geographical characteristics in shaping deposition outcomes.

- **4.4.1. Sensitivity to Erodibility**

In this comprehensive examination of the erodibility parameter's impact on cumulative re-sedimentation across various catchments, we scrutinize distinct DEM with similar resolutions but different extents. The observed trends unveil a cohesive response to changes in the erodibility parameter across these catchments (Figure 31). The re-sedimentation behaviour, represented by the trend lines, demonstrates a generally close pattern. Interestingly, the graphs for all catchments are closely aligned, indicating a uniform sensitivity to alterations in the erodibility parameter. This uniformity suggests a consistent and proportional increase in sedimentation across the catchments as the erodibility parameter varies.

However, amidst this overarching similarity, subtle distinctions emerge. Entire Bergantes catchment exhibits the least sensitivity to changes in erodibility, as evidenced by its shallower trend line slope. In contrast, Prado stands out with the highest sensitivity, displaying a steeper slope in its trend line. The remaining catchments, including Guadalhorce, Bergantes up, and both Sabinal scenarios, fall in between, showcasing intermediate sensitivity. we can understand again larger extents shows lower sensitivity. These nuanced variations shed light on the intricate interplay between catchment-specific characteristics and the erodibility parameter's influence on sedimentation.

Figure 31. Total Deposition results for Erodibility parameter variation in all comparative catchments DEM

- **4.4.2. Sensitivity to Sedimentiability**

The sedimentiability parameter's impact on deposition reveals distinct patterns across these catchments. Guadalhorce catchment stands out prominently, showing an absence of sensitivity to alterations in the sedimentiability parameter (Figure 32). This is evident in the nearly horizontal trend line, suggesting that changes in this parameter have negligible effects on sedimentation in Guadalhorce. Conversely, Bravura, Prado, and the aggregated 25m Sabinal DEM exhibit pronounced sensitivity, reflected in steeper trend lines. Bravura and Prado, in particular, demonstrate the highest sensitivity to changes in sedimentiability. Following closely, Bergantes up, Entire Bergantes, and Sabinal with a 25 m resolution display intermediate sensitivity, each with a unique slope in their trend lines.

This nuanced analysis underscores the interplay between catchment-specific characteristics and the sedimentiability parameter's role in governing deposition. As we progress through subsequent analyses, a holistic understanding of sedimentation dynamics across these diverse landscapes will continue to unfold.

Total Sedimentation result for Sedimentiability parameterchange

Y-axis: Modelled output change [%]

X-axis: input parameterchange [%]

Legend:
- 25 m sabinal
- 25(5) m sabinal
- 25 m Bravura
- 20 m prado
- 20 m bergantes up
- 20 m entire bergantes
- 25 m Guadalhorce

Figure 32. Total Deposition results for Sedimentiability parameter variation in all comparative catchments DEM

- **4.4.3. Sensitivity to Annual Rainfall change**

In unraveling the intricacies of sedimentation, our attention turns to the influence of the annual rainfall parameter across various catchments. The examination of these catchments reveals a consistent and discernible increasing trend in sedimentation concerning alterations in the annual rainfall parameter (Figure 33). Guadalhorce and Sabinal with a 25 m resolution stand out as the most sensitive, displaying a linear increase in sedimentation with changing rainfall levels. On the other hand, upper Bergantes catchment and the entire Bergantes region exhibit intermediate

sensitivity, portraying a steady rise in sedimentation. Contrarily, Aggregated Sabinal DEM, Bravura DEM, and Prado DEM showcase less sensitivity to variations in the annual rainfall parameter. This analysis underscores the nuanced interplay between catchment characteristics and the influence of annual rainfall on sedimentation patterns.

Figure 33. Total Deposition results for Annual Rainfall parameter variation in all comparative catchments DEM

- **4.4.4. Sensitivity to Discharge Exponent**

In exploring the discharge exponent parameter's impact on sedimentation, distinct patterns emerge across catchments and resolutions (Figure 34). The Bravura DEM at 25 m resolution exhibits a

unique behaviour, characterized by a substantial alteration range and an initial increase followed by a sharp decrease. The Prado DEM at 20 m resolution displays a noteworthy variation, with a distinctive pattern of decrease with the highest range of variation in comparison to others.

Guadalhorce's 25 m resolution DEM showcases an intriguing response, first escalating up to the base scenario and then gradually decreasing. Bergantes Up at 20 m resolution demonstrates a distinct alteration pattern, with an initial increase, followed by a decline towards the base scenario, and finally a subtle decrease beyond the base scenario. Entire Bergantes, also at 20 m resolution, displays a substantial variation, with an initial rise, a subsequent decrease towards the base scenario, and a minimal decline beyond the base scenario.

Sabinal's 25 m resolution DEM illustrates a consistent increasing trend in sensitivity, while the aggregated 25 m resolution from 5 m resolution displays a substantial variation, albeit following a different trajectory compared to other catchments. These diverse patterns underscore the nuanced responses of different catchments to variations in the discharge exponent parameter.

Figure 34. Total Deposition results for Discharge exponent parameter variation in all comparative catchments DEM

● **4.4.5. Sensitivity to Slope Exponent**

Examining the impact of the slope exponent parameter on sedimentation patterns in various catchments reveals a shared behavior among all DEM up to 80% of the base scenario, signifying minimal deposition during this initial phase (Figure 35). Subsequently, distinctive responses emerge, highlighting the sensitivity of the deposition process to alterations in the slope exponent parameter. Prado DEM exhibits the most pronounced alterations, showcasing a heightened sensitivity to changes in the slope exponent. Bravura DEM, although less responsive than Prado,

still demonstrates significant sensitivity. Aggregated Sabinal follows, indicating substantial variations but to a lesser extent than Prado and Bravura. After the base scenario, Sabinal DEM introduces unexpected fluctuations, deviating from the anticipated trend, while the other three DEM display a subtle decreasing behaviour. This nuanced interplay between the slope exponent parameter and sedimentation response underscores the complex dynamics within catchment systems.

Figure 35. Total Deposition results for Slope exponent parameter variation in all comparative catchments DEM

- **4.4.6. Sensitivity to flow Convergence Factor**

Analyzing the influence of the convergence factor parameter on deposition outcomes across various catchments reveals intriguing patterns (Figure 36). Notably, Prado catchment's DEM stands out with its distinctive linear decrease in sedimentation as the convergence factor parameter varies. In contrast, the remaining catchments, including Bravura, Guadalhorce, Bergantes up, and Sabinal, exhibit minimal sensitivity to changes in the convergence factor. Bravura's deposition response demonstrates a slight decrease, but the overall impact is negligible. Guadalhorce, Bergantes up, and Sabinal catchments, alongside their aggregated 25m resolution from 5m, maintain a stable sedimentation trend, showing little to no sensitivity to variations in the convergence factor parameter.

Figure 36. . Total Deposition results for Convergence factor parameter variation in all comparative catchments DEM

Chapter 5

Discussion

In this discussion section, we delve into a comprehensive analysis of the erosion and sedimentation outputs generated for the Sabinal catchment DEM, as well as comparative catchments, aiming to elucidate the intricate relationships between DEM and landscape evolution processes. Through an in-depth examination of the model outputs, we aim to provide valuable insights into the sensitivity of erosion and sedimentation modelling to changes in DEM resolution and other key parameter. By systematically evaluating the results obtained for each catchment, we endeavor to unravel the complexities of landscape dynamics and offer valuable contributions to the field of geomorphology.

- **5.1. Average Sensitivity of Erosion Outputs for Sabinal Catchment DEM**

In this section, the focus lies on the average sensitivity for erosion outputs for the Sabinal catchment (Table 4), facilitating a thorough examination of the model's response to variations in DEM and other pivotal parameter. The table presents a detailed analysis of the average sensitivity

exhibited by each DEM to the parameter under scrutiny, enabling a comparative evaluation of their impact on erosion dynamics.

Table 4. Average erosion sensitivity outputs for Sabinal catchment (%)

	Erodibility	Sedimentiability	rainfall	Discharge exponent	slope exponent	Convergence factor
5 m	27.98	0.00	28.50	0.00	0.70	0.08
10 m	27.98	0.00	28.50	3.11	1.06	0.06
25 m	27.45	0.00	29.03	5.96	2.84	0.40
10(5) m	27.72	0.13	28.43	5.78	2.05	0.02
25(5) m	27.56	0.05	28.88	9.38	2.86	0.35

It is noteworthy that the average sensitivity of each DEM remains within a similar range for alterations in the same parameter. This consistency in sensitivity values across DEM is an expected outcome, particularly in the context of erosion modelling within the LAPSUS landscape evolution model. In LAPSUS, the erosion process operates as a direct function, primarily affecting individual cells within neighboring areas. Consequently, the uniformity observed in sensitivity values underscores the robustness and reliability of the erosion modelling outcomes within the Sabinal catchment.

- **5.2. Average Sensitivity of Erosion Outputs for Sabinal Catchment DEM**

This section presents a detailed examination of the average deposition sensitivity outputs for various DEM within the Sabinal catchment (Table 5). By quantifying the average sensitivity of

each DEM across different parameters, this analysis offers valuable insights into the deposition dynamics within the catchment.

Table 5. Average sedimentation sensitivity outputs for Sabinal catchment (%)

	Erodibility	Sedimentiability	rainfall	Discharge exponent	slope exponent	Convergence factor
5 m	28.40	20.46	6.85	20.46	419.34	14.25
10 m	28.82	26.24	1.31	776.84	791.11	4.00
25 m	27.52	3.40	26.14	31.85	49.11	1.47
10(5) m	27.88	22.02	6.94	170.24	193.93	3.01
25(5) m	27.68	18.92	10.85	97.36	125.08	0.13

Notably, there is a lack of consistency in average sensitivity values for the same parameter across different DEM, particularly evident in discharge exponent and slope exponent parameter. This inconsistency is expected in sedimentation results due to the indirect nature of the sedimentation process within the LAPSUS model. Unlike erosion, which involves direct interactions within neighboring cells, sedimentation is influenced by multiple flow factors, potentially involving a larger number of cells. Consequently, variations in discharge and slope exponent parameter can have a more pronounced impact on sedimentation outcomes. Despite this variability, erodibility and convergence factor parameter exhibit relatively consistent average sensitivity values across all DEM. This observation underscores the complex interplay between DEM characteristics and sedimentation modelling outcomes.

- **5.3. Comparison of Results between Original and Aggregated DEM**

This subsection presents a comparison of the results obtained from the original DEM and their aggregated counterparts, focusing on resolutions of 10 m and 25 m. Additionally, the comparison includes results derived from aggregating DEM at 10 m and 25 m from a finer resolution of 5 m. Through this comparative analysis, we aim to assess the impact of DEM aggregation on modelling outcomes, particularly in the context of erosion (Table 6) and sedimentation (Table 7) processes.

Table 6. Average sensitivity results in erosion for original and aggregated DEM

		Erodibility	Sedimentiability	rainfall	Discharge exponent	slope exponent	Convergence factor
Erosion	10 m	27.98%	0.00%	28.50%	3.11%	1.06%	0.06%
	10(5) m	27.72%	0.13%	28.43%	5.78%	2.05%	0.02%
	25 m	27.45%	0%	29.03%	5.96%	2.84%	0.40%
	25(5) m	28%	0.05%	28.88%	9.38%	2.86%	0.35%

In examining the erosion results comparing original and aggregated outputs, a notable consistency emerges. The average sensitivity for each DEM, concerning the same parameter, falls within a similar range across both original and aggregated datasets. This consistency underscores the robustness of the erosion modelling outcomes, irrespective of resolution alterations through

aggregation. The findings suggest that the process of aggregating DEM at different resolutions does not significantly impact the sensitivity of erosion modelling parameter. This observation aligns with the expectations outlined in the thesis, indicating that erosion processes, being direct and involving neighboring cells, exhibit consistent behavior across varying resolutions and aggregation techniques within the LAPSUS model.

Table 7. Average sensitivity results in sedimentation for original and aggregated DEM

		Erodibility	Sedimentiability	rainfall	Discharge exponent	slope exponent	Convergence factor
Sedimentation	10 m	28.82%	26.24%	1.31%	776.84%	791.11%	4.00%
	10(5) m	27.88%	22.02%	6.94%	170.24%	193.93%	3.01%
	25 m	27.52%	3.40%	26.14%	31.85%	49.11%	1.47%
	25(5) m	27.68%	18.92%	10.85%	97.36%	125.08%	0.13%

In examining the average sensitivity results for sedimentation across aggregated and original DEM of 10m and 25 m resolutions, a notable lack of consistency in sensitivity emerges, particularly concerning deposition parameter such as discharge and slope components. While parameter like erodibility and convergence factor demonstrate relatively consistent sensitivities, sedimentation and annual rainfall parameter exhibit moderate variations. Interestingly, there is no discernible correspondence between the sensitivity of original and aggregated DEM results, indicating that

alterations in DEM resolution do not consistently align with changes in sensitivity. For instance, while the original 10 m DEM shows higher sensitivity compared to aggregated one, the opposite holds true for 25 m DEM resolution, where aggregated DEM exhibits higher sensitivity than the original counterpart. This disparity underscores the complex interplay between DEM resolution and sensitivity responses in erosion and sedimentation modelling within LAPSUS.

- **5.4. The most and the least sensitive DEM resolution for the Sabinal catchment**

To discern the overall sensitivity of DEM to different parameters in the analysis of the Sabinal catchment, the following tables outlining the most and least sensitive DEM for erosion (Table 8) and deposition (Table 9) scenarios are provided.

Table 8. The most and the least sensitive DEM for erosion in the Sabinal catchment

Parameter	Most Sensitive DEM	Least Sensitive DEM
Erodibility	Constant sensitivity	Constant sensitivity
Sedimentiability	No Sensitive	No Sensitive
Annual Rainfall	Constant sensitivity	Constant sensitivity
Discharge Exponent	Coarse Resolution	Fine Resolution
Slope Exponent	Coarse Resolution	Fine Resolution
Convergence Factor	Coarse Resolutions	Fine Resolutions

Table 9. The most and the least sensitive DEM for sedimentation in the Sabinal catchment

Parameter	Most Sensitive DEM	Least Sensitive DEM
Erodibility	Constant sensitivity	Constant sensitivity
Sedimentiability	10m Resolution	25m Resolution
Annual Rainfall	25m Resolution	10m Resolution
Discharge Exponent	10m Resolution	5m Resolution
Slope Exponent	10m Resolution	25m Resolution
Convergence Factor	5m Resolution	25m Resolution

The sensitivity analysis results for erosion and deposition processes reveal distinctive patterns in how different parameters affect DEM of varying resolutions within the Sabinal catchment. Erosion, being a direct process, exhibits consistent trends across different resolutions, where coarser DEM generally display higher sensitivity to parameters such as discharge exponent, slope exponent, and convergence factor. Conversely, parameters like erodibility and annual rainfall demonstrate consistent sensitivity across all resolutions, while sedimentibility shows negligible sensitivity overall. In contrast, the deposition process, being more indirect, yields varied and unpredictable sensitivity patterns across resolutions and parameters. This discrepancy underscores

the nuanced nature of sedimentation dynamics, where the relationship between DEM resolution and parameter sensitivity is less straightforward compared to erosion.

- **5.5. Average Sensitivity for Erosion and Deposition Outputs of Comparative Catchments DEM**

In exploring the erosion sensitivity across comparative catchments, the analysis delves into how various parameters influence landscape evolution within different extents but in the same range of DEM resolution. In scrutinizing the average sensitivity of DEM resolutions across comparative catchments, our focus is to discern any discrepancies in erosion and deposition modelling outcomes. We aim to ascertain whether DEM with similar resolutions and parameter settings yield comparable results in landscape evolution.

Table 10. Erosion outputs for all comparative catchments

	Erodibility	Sedimentibility	Rainfall	Discharge exponent	Slope exponent	Convergence factor
Bravura(25m)	27.63%	0.02%	28.84%	14.01%	5.31%	0.13%
Prado(20m)	27.09%	0.03%	29.37%	11.29%	6.77%	0.49%
Guadalhorce(25m)	23.43%	0.06%	24.09%	6.17%	3.03%	0.01%
Bergantes Up(20m)	27.06%	0.08%	27.90%	5.22%	1.91%	0.10%
Entire Bergantes(20m)	20.35%	0.36%	21.07%	246.40%	3.95%	0.57%
Sabinal 25m	27.45%	0%	29.03%	5.96%	2.84%	0.40%
Sabinal 25(5)m	28%	0.05%	28.88%	9.38%	2.86%	0.35%

Notably, our analysis reveals a notable consistency in erosion sensitivity across catchments (Table 10), underscoring the robustness of the modelling approach. However, anomalous behaviour is observed in the discharge component parameter, particularly evident in the Entire Bergantes catchment.

Table 11. Deposition outputs for all comparative catchments

	Erodibility	Sedimentibility	Rainfall	Discharge exponent	Slope exponent	Convergence factor
Bravura(25m)	27.92%	18.28%	11.08%	251.22%	221.64%	1.99%
Prado(20m)	31.36%	18.19%	7.31%	226.74%	319.92%	23.17%
Guadalhorce(25m)	23.57%	0.13%	24.05%	32.81%	36.73%	0.01%
Bergantes Up(20m)	27.43%	9.38%	19.70%	56.31%	64.29%	0.37%
Entire Bergantes(20m)	22.41%	5.50%	18.04%	47.45%	51.28%	0.33%
Sabinal 25m	27.52%	3.40%	26.14%	31.85%	49.11%	1.47%
Sabinal 25(5)m	27.68%	18.92%	10.85%	97.36%	125.08%	0.13%

In examining the average sensitivity of DEM across parameter variations for deposition in comparative catchments (Table 11), we aim to evaluate the coherence of modelling outcomes. The table highlights a pronounced inconsistency in deposition results, particularly notable in the discharge and slope exponent parameters. Conversely, sedimentiability and convergence factor parameters exhibit relatively lower levels of inconsistency across catchments. Sabinal catchemt with a smallest extent and the Guadalhorce catchment with largest extent show that the sensitivity of DEM resolution does not have specific relationship with extent.

- **5.6. Limitations**

A noteworthy limitation of this study is related to the use of DEM with varying resolutions and extent. While this approach allows us to explore how changes in resolution and extent affect landscape model outcomes, it's essential to recognize that resolution is just one aspect of data quality. The DEM used in this analysis may have been derived from different data sources, collected through various acquisition methods, and subjected to distinct preprocessing procedures. These inherent variations in data quality, accuracy, and source could introduce uncertainties that extend beyond resolution alone. Consequently, the potential influence of these data-related factors on our sensitivity analysis should be acknowledged.

Furthermore, it's important to acknowledge the inherent limitations associated with the LAPSUS model itself. This includes the model's underlying assumptions, simplifications, and its ability to faithfully represent complex real-world landscape processes. While LAPSUS is a valuable tool for our study, these model-related limitations may affect the precision and generalizability of our findings. Recognizing these constraints is crucial for a comprehensive interpretation of the study's results and their implications.

The methodology employed in this study is designed to rigorously assess the sensitivity of the LAPSUS erosion-deposition model to variations in key input parameter and DEM resolutions. By systematically altering one parameter at a time while maintaining a consistent base scenario across multiple catchments, we aim to comprehensively understand the model's response to changes in erosion and sedimentation dynamics. The use of various DEM with different resolutions and extent adds an essential dimension to our analysis, allowing us to explore the influence of data quality and accuracy on model outcomes. While this approach presents opportunities for robust insights, it is important to acknowledge the potential limitations associated with data variations and model

assumptions. In the following sections, we delve deeper into the details of the LAPSUS model outputs and results.

Chapter 6

Conclusion

The resolution of DEM holds importance in landscape evolution modelling, particularly concerning erosion and sedimentation dynamics. The variation in DEM resolution encompasses differences in elevation between neighbouring cells, raising a central inquiry into how these discrepancies impact modelling outcomes. In this study, the LAPSUS5 model served as the foundation, grounded in the principle of potential energy within flowing water driving sediment transport, with additional emphasis on the continuity equation to elucidate sediment movement. The focus was directed towards the variation of six crucial parameters within the model: erodibility, sedimentiability factor, annual rainfall amount, discharge exponent, slope exponent, and the convergence factor parameter, This scrutiny aimed to unravel the intricate relationship between DEM resolution and its effects on erosion and sedimentation modelling.

A standardized base scenario was established, maintaining uniform parameter across all DEM, facilitating a systematic investigation into the response of DEM to parameter variations. Each parameter was systematically adjusted within a range from -45% to +45% of the base scenario, with incremental steps of 2.5%, enabling a comprehensive analysis of DEM sensitivity. The study's focus narrowed onto the Sabinal catchment DEM, comprising original DEM at resolutions of 5 m, 10 m, and 25 m. Additionally, aggregated DEM were utilized, synthesized from 5-meter resolution DEM to form 10-meter and 25-meter resolution DEM.

The study was bifurcated into two distinct phases: erosion and sedimentation, each analyzed independently to unravel the differential responses of DEM to parameter variations. In the erosion phase, the behavior of Sabinal DEM exhibited a more straightforward and cohesive pattern, with varying DEM demonstrating comparable sensitivities, albeit not identical. This coherence can be attributed to erosion being a direct process, primarily driven by flow routing on neighboring cells, with flow directed towards the lowest cell for erosion. However, elucidating similarities in DEM behavior across different parameter posed challenges, particularly concerning discharge and slope exponent parameter. Conversely, the deposition phase showcased greater inconsistency, attributable to the indirect nature of deposition processes. Unlike erosion, deposition entails flow routing across multiple neighborhood cells, influenced by erosion outcomes. Consequently, the deposition process diverges from erosion, resulting in varied DEM responses across parameter and rendering comparisons between DEM more intricate.

The analysis of the Sabinal catchment revealed distinct trends in the sensitivity of DEM to erosion and deposition processes. In erosion modelling, while most parameter exhibited heightened sensitivity to coarser resolutions, certain nuances were observed, suggesting a varied impact across parameter. However, the behavior of DEM diverged significantly in deposition modelling, defying

conventional patterns observed in erosion. Notably, disparities were most pronounced for parameter such as slope exponent and discharge exponent, indicating complex interactions within the deposition process. Furthermore, when comparing original and aggregated DEM, each exhibited unique behaviors, precluding definitive conclusions regarding their relative sensitivity.

Following the examination of the Sabinal catchment, a natural curiosity emerged regarding the potential outcomes of employing DEM from different catchments with similar resolutions on different extents. This led to a subsequent analysis of comparative catchments, each possessing distinct characteristics yet sharing comparable DEM resolutions. Despite observing a more consistent average range of sensitivity compared to the Sabinal catchment, discerning uniform behavior among DEM from different catchments proved challenging. Indeed, while the average sensitivity exhibited greater consistency, variations persisted across different catchments, highlighting the intricate interplay between catchment characteristics and DEM resolution effects. Thus, while the comparative analysis yielded insights into broader trends, it reaffirmed the need for caution when extrapolating findings to diverse geographical contexts.

In conclusion, this study underscores the distinctiveness of DEM behavior, particularly concerning erosion and deposition modelling within the LAPSUS framework. While erosion responses tend to exhibit a degree of predictability, deposition behaviors remain more variable and less easily discernible across different DEM resolutions. Consequently, there is a pressing need for further investigations in this domain, encompassing a broader spectrum of parameter and encompassing diverse catchment scenarios. Such endeavors hold the promise of elucidating more specific relationships governing the sensitivity of DEM resolutions, thus advancing our understanding of landscape evolution processes.

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