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MODEL FOR SIMULATION OF GRANULOMETRIC DISPERSION IN RIVER ENVIRONMENT

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Abstract: The granulometric dispersion is an important element in the constitution of fluvial systems, since the processes that determine the granulometric dispersion are the same that act by molding the shape and geometry of the fluvial channels and influence the constitution of the relief. When a landscape is simulated using a Landscape Evolution Model (LEM), only a topographic surface is commonly generated, and in the case of a river system, a visualization of the distribution of deposits may be necessary to better understand the behavior and trends of this system. In this work we propose a model of particle size dispersion in river systems based on the Shear Stress theory with open source code and implementation with the Landlab library for use together with a LEM. The model simulates the location of fluvial deposits and the grain size found in these deposits and a case study in the Pirati Basin area, RS, Brazil, demonstrated how the granulometric dispersion behaves in different time steps through the application of an LEM.

Keywords: Sedimentary dispersion, fluvial environment, Landlab, grain size, Landscape evolution model.

INTRODUCTION

Models are abstractions of reality in order to analyze certain processes in their particularities. Using geological models we can simulate processes and obtain resulting scenarios, through the application of analytical tools (Paola 2000; Dalmasso et al. 2001). The application of Landscape Evolution Model (LEM) to watersheds can provide additional information about the processes that interact to transfer mass from one location to another, shaping the surface of a river system. The possibility of visualizing graphical representations of the evolution of a basin increases the ability to interpret possible changes in the surface and to quantify hypotheses about river dynamics (Nones 2020).

A LEM consists of the numerical representation of flow and processes applied to a terrain. According to (Salles and Hardiman 2016), an LEM simulates, based on physical laws and principles, geomorphological processes acting on the Earth's surface. When coupled with enhanced observation and qualitative and quantitative modeling of geological processes, these models are very useful for advancing understanding of the mechanisms that control watershed form and function (Tucker and Hancock 2010).

By having as a characteristic the possibility of simulating several integrated processes, LEMs act as important aids for an increasingly improved quantitative characterization of terrain and process. Thus, they provide support for increasingly better theories that describe the continuous modification of topography and the mechanisms that drive the varied processes of modification (Tucker and Hancock 2010; Barnhart et al. 2019).

The alluvial channels of a river have their geometry and morphology defined as a consequence of the transport, deposition and remobilization of the sediments they transport. Sediment transport depends on characteristics such as water discharge, morphology and slope of channels and sediment discharge, being an iterative system. The morphodynamics of a river is the expression of erosion, transport and deposition of material from the bed and the study of how these elements interact (Church 2006; Church and Ferguson 2015). The shape of the channel thus becomes the expression of the transport laws that govern this channel. It is assumed that these laws operate mechanistically enough that cause relationships can be investigated through modeling (Dietrich et al. 2003). The modeling and quantification of these processes allow an increase in knowledge on the subject, which helps in the development of more robust hypotheses and predictions about the behavior of river systems (Dalmasso et al. 2001; Nones 2020; Paola 2000), the application in a LEM is important because it is possible to simulate these elements acting together and in temporal evolution, allowing the projection of future scenarios and insights into the processes.

In this work, a sedimentary dispersion model capable of simulating the dispersion of grains in a fluvial environment with alluvial channels is proposed. The model aims to be applied together with an LEM, simulating the active geomorphological processes and the resulting sedimentary dispersion in different time steps. Bibliographic data from the works of Leopold and Maddock (1953), Andreadis et al. (2013), Mitchell (2000), Le Roux (1998), and Montgomery et al. (1996), and its implementation was made in Python language using the Landlab library, by (Adams et al. 2017), and depends on the execution of some of its components for operation. Tests were carried out simulating the granulometric dispersion and the evolution of the landscape of the Piratini Basin area, in the State of Rio Grande do Sul (RS).

LANDLAB

Landlab, developed by (Adams et al. 2017), is an open source Python language library for numerical modeling of the Earth's surface dynamics. Using the components available in Landlab, it is possible to simulate the evolution of the topographic landscape through time with the application of differential equations that simulate surface, tectonic and isostatic processes using differential equations and concepts of geomorphology, hydrology, glaciology and stratigraphy.

The simulation of a LEM using Landlab takes place through the application of the components chosen by the user in a grid, which can be created as a matrix, or generated from the incorporation of a Digital Elevation Model (DEM) in Raster format.

A DEM represents the topography of the ground surface, usually by a finite set of elevation points, in data organized in the form of a matrix. DEMs are used as a basis for applying quantitative methods of topographic analysis and modeling and the interactions of landscape components (Schwanghart and Kuhn 2010).

In this work DEMs are used as a basis for the application of LEM and dispersion algorithms. The Piratini Basin was chosen for the study and DEMs with regular spacing of 90 m, 190 m and 360 m were used.

MODEL BUILDING COMPONENTS

The result of applying granulometric dispersion depends on how the LEM will be built and as a result the topography will be shaped, which in this case is done through the Landlab components. This section covers the main functionalities of the components that were used in this model. The previous execution of the flow routing components of the Landlab library, FlowDirectors and FlowAccumulator, is necessary for the simulation of dispersion, while the other components (DepressionFinderAndRouter, FastScapeEroder, ErosionDeposition and LinearDiffuser) were used to build the LEM and can be adjusted or modified. replaced according to what you want to model.

DepressionFinderAndRouter, FlowDirectors, FlowAccumulator

The Landlab DepressionFinderAndRouter component is based on the work of (Tucker et al. 2001) and works by mapping depressions on a topographical surface and routing the flow to an exit, allowing the flow to continue. The Landlab FlowDirectors component, based on (O'Callaghan and Mark 1984), is used as a tool to determine flow directions in a topographic grid. There are variations in the method to be used, in this work the eight neighborhoods method (D8) was used, which finds the neighbor with the steepest slope among the eight neighborhoods of a cell in the grid and directs the flow to this cell.

FlowAccumulator is a Landlab component based on the work of (Braun and Willett 2013) that acts as a tool to accumulate flow and calculate the drainage area. This component depends on the previous FlowDirectors execution as it uses the flow directions found.

FastScapeEroder

The Landlab FastScapeEroder component calculates river erosion using Stream Power theory. The approach of (Braun and Willett 2013) is used to calculate the amount of erosion in each cell in a grid, according to the Stream Power equation (equation 1):

$$E = KA^{m}S^{n} - threshold$$

Where K is the erodibility, A is the drainage area, S, the slope, m, a user-defined constant (related to the drainage area), n, a user-defined constant (related to slope) e , a user defined threshold.

In this work, the component was used to extract an initial drainage network, with standard Landlab parameters.

ErosionDeposition

ErosionDeposition is a component written by (Barnhart et al. 2019) and is a mesoscale erosion/deposition model, which takes into account the mass balance for the flow. In this model the rate of change of topography is the sum of the erosion/deposition and gravitational processes (slope) terms. Erosion is calculated in the model using the Stream Power equation (equation 1)

Deposition is calculated in the style of (Davy and Lague 2009), using equation 2:

$$d = d^{\star}\frac{v_s q_s}{q}$$

Where is water discharge, a grid generated by the component: *FlowAccumulator*; q_s is the sediment load of the river per unit of river width; v_s is the volume of the average vertical velocity of the particles in the river, being defined by the user ; d^⋆ is assigned as 1.

The main parameter of the component to define the deposition style is v_s, where $v_s > 1$ determines erosion limited by transport and $v_s > 1$ determines a limited erosion by abrasion.

LinearDiffuser

Landlab LinearDiffuser component models the processes of slope mass movement by implementing linear diffusion, with equations based on the work of (Culling 1963). The component has different method options to represent the flows and the deposit parameter, which must be used as TRUE for transport-limited deposition styles and FALSE for abrasion-limited erosion.

PARTICLE SIZE DISPERSION MODEL

The granulometric dispersion modeling aims to visualize the grain size that will be present in each cell in a grid. The calculation for this consists of finding the Shear Stress for each cell and then relating it to the corresponding grain size.

Shear Stress

In a sediment bed where there is no moving material, as the fluid passing through it increases its velocity (or stress) on this bed, a point is given at which any increase in these conditions will cause the movement and transport of the bed material. The moment just before the start of the movement is called the threshold and the slight increase in speed or stress will generate the start of the movement (Miller, McCave, and Komar 1977).

(Shields 1936) defined the onset of motion, the state in which grains begin to move, as a matter of how great is the resistance of the grain to movement and how great is the force exerted by the flow on the upper layer of grains. Grain resistance is the force required to dislodge a grain from a bed of uniform grains and is proportional to the weight of the grain.

The competence of a stream is its ability to mobilize sediments according to their size. Competence is quantified by the Shields number, a dimensionless measure of the shear stress exerted by the flow in the bed. The shear stress can be defined by the force per unit area exerted on the flow boundary, being the boundary condition for dragging sediments of a certain size, that is, as a limiting ratio between the flow drag force and the sediment inertia (Church 2002). Shear stress is implemented as:

$$T^* = pgdS$$

Where, ρ is the density of the fluid, g is the acceleration of gravity, d the depth of flow in m, S the gradient of the channel or slope. The fluid density is defined by the user, the default value being ρ=1050 (kg/m^3); gravity has default value g=9.80665 m/s^2 which can be changed by user. S is the gradient or slope that is generated by the component: *FlowDirectors*.

Depth calculation using flow

To calculate the Shear Stress in each cell it is necessary to know the depth, d, of each cell. This was calculated using the formula of (Leopold and Maddock 1953) which uses the flow:

$$d = cQ^f$$

Where Q is the flow in m^3/s, c a variable between [0.12, 0.63] and f a variable between [0.30 ± 0.01] according to (Andreadis, Schumann, and Pavelsky 2013).

The flow can be calculated using the equation proposed by (Howard and Kerby 1983), which determines that the dominant discharge is proportional to the power of the drained area:

$$Q = kA^e$$

Where k is the proportionality coefficient, A, the accumulation in m^2 and the value of the exponent is equal to 1. According to (Mitchell 2000) the variable k must be in the range between 0.00084 and 0.3.

Finally, equation can be rewritten by substituting Q:

$$d = c(kAe)^f$$

Where c, f and k are user defined and A is the drainage area grid generated by the component: *FlowAccumulator*.

Correlation of Shear Stress with grain size

The shear stress is calculated for each cell in the grid, thus, using a correlation of the shear stress with the grain size, it is possible to determine which grain is potentially deposited for each cell in the grid.

The correlation between grain size and shear stress was obtained from the work of (Le Roux 1998) and is given according to table 1:

Shear Stress		grain size (cm)
58.275		0.8000
29.138		0.4000
14.503		0.2000
6.6074		0.1000
2.8541		0.0500
2.1964		0.0250
1.7423		0.0125
1.2710		0.0063
0.8492		0.0031

Table 1- Correlation between grain size and shear stress (Le Roux 1998).

Grain size values were discretized according to size classification (Wentworth 1922) and adjusted for better display (Table 2):

Size	Sediment	Code
<= 0.004	Clay	1
0.004 - 0.062	Silt	2
0.062 - 0.25	Thin sand	3
0.25 - 0.5	Medium Coarse Sand	4
0.5 -1	Coarse sand	5
1-4	Granule	6
>4	Top of Granule	7

Table 2- Discretization of sediment grain size, corresponding grain type and respective code.

Critical slope

The critical gradient was inserted as a boundary for deposition of two grains, occurring below the alluvial channels. The calculation for the critical gradient is based on (Montgomery et al. 1996), resulting from the deduction of equality of equations for transport capacity and sediment supply, and is given by the equation:

$$S_c = \left[\left(\frac{b}{k}\right) A^{p-m}\right]^{\frac{1}{n}}$$

Where A is the drainage area, and b, k, p, m e n são empíricas variáveis adimensionais (Milliman and Syvitski 1992) whose standard values were used for: b = 0.000008, k = 0.001, p = 0.3, m = 0 .4 and n = 1.

Second (Montgomery et al. 1996), these variables incorporate local transport capacities, sediment supply, geology, and climate. According to this model, flooding can occur when the observed gradient is less than the calculated critical gradient.

The parameters b, I think are constant, while the parameters k can be altered by the user; m must be between 0.3 and 0.5; k is related to erodibility.

SIMULATION WITH A CASE STUDY OF THE PIRATINI BASIN

The Piratini Basin area was used to carry out two granulometric dispersion tests. A DEM was used in asc format containing the area of the basin, with dimensions 114,030 m (ax x), 88,830 m (ax y) and 90 m cells, obtained from (Reuter, Nelson, and Jarvis 2007), which was reshown for cell sizes of 180 µm and 360 µm.

Three simulations were carried out, one for each different cell size of the DEM, using the LEM to simulate the topographic evolution in 10,000 and 50,000 years in the basin area, only varying the cell size of the imported DEM. The parameters used for the simulations (table 3) do not vary.

COMPONENT	PARAMETER	VALUE
Erosion Deposition	K	0.0005
		0.00001
		0.5
		1
Linear Diffuser	Deposit	false
	Diffusivity	0.1
Fast Scape Eroder		0.001
		0.5
		1
	threshold	0

Table 3- Non-LEM parameters used to simulate the topographic evolution of the Piratini Basin.

The granulometric dispersion was simulated in the current area of the basin and in the simulated topography in 10,000 and 50,000 years of evolution for the three cell sizes using the standard parameters described in session 4. The simulation was carried out following the steps of the flowchart (Figure 1).

Firstly calculated shapes to the drainage area or SteepestSlope using the FlowAccumulator and FlowDirectors

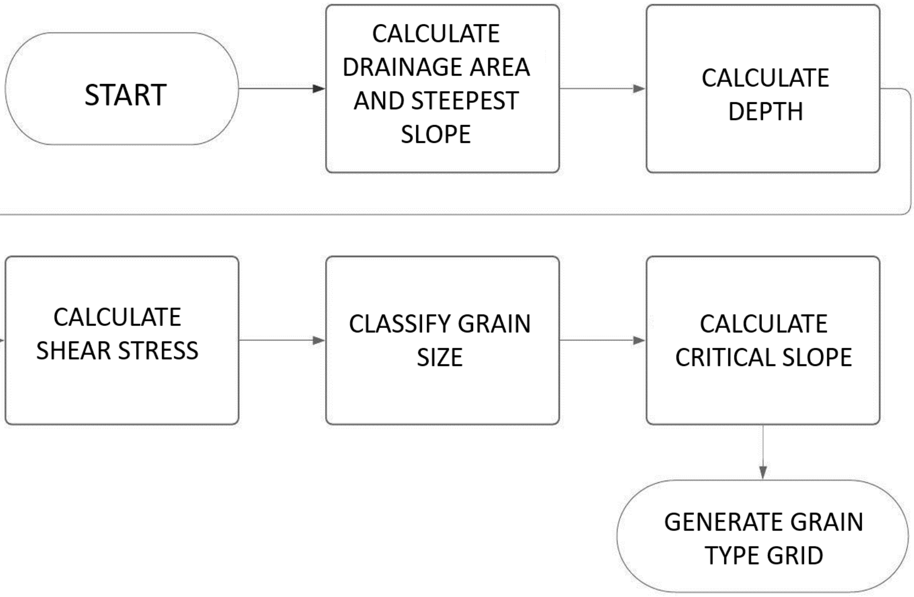


Figure 1- Flowchart with the steps executed to classify the type of grain.

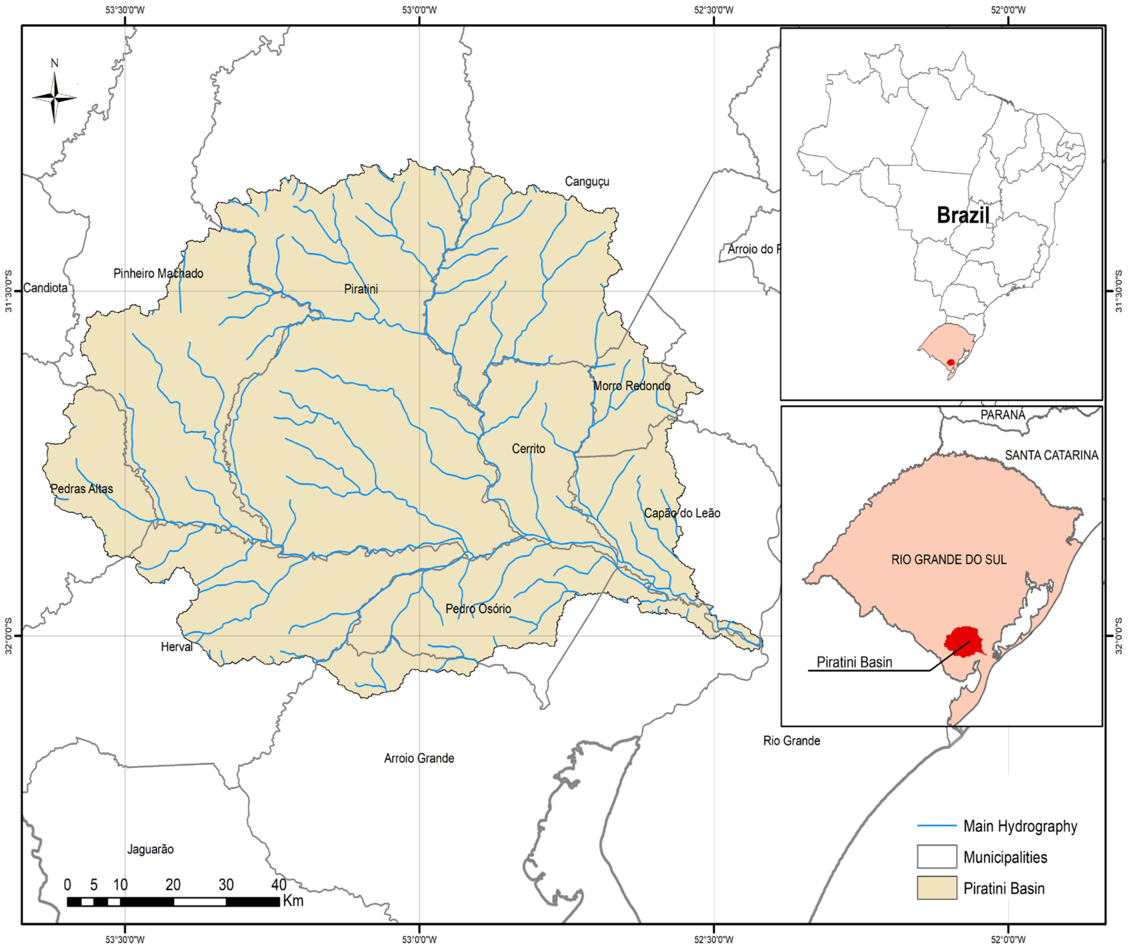


Figure 2 - Location of the Piratini Basin, with its main hydrography, municipal limits and location in the Brazilian territory and state of Rio Grande do Sul.

components. Apos was calculated at depth and immediately or Shear Stress for each non-grid cell. Using the correlation presented in session 4.3, the values obtained for the Shear Stress were used to classify two grains in all areas. The areas of occurrence of two alluvial deposits were defined using the calculation of the Critical Gradient (session 4.4) and finally the grid named Grain Type was generated in asc format.

CONTEXTUALIZATION OF THE PIRATINI BASIN

The hydrographic basin of the Piratini River (Bacia do Piratini) is located in Brazil, in the south of the state of Rio Grande do Sul, between the geographic coordinates 31º 00' to 32º 10' latitude South and 52º 10' to 53º 50' West. The area of the basin is 5,549 km^2, its tributaries are distributed in a dendritic pattern and its shape is joined to a lake (Figure 2).

The Piratini Basin is mostly on the crystalline basement of Rio Grande do Sul, being predominantly composted in its geology by terrains of the Mantiqueira province, with a predominance of granites and metamorphic rocks. A smaller portion of the basin is located on the coastal plain and is composted by sedimentary deposits (CPRM 2005)(figure 3).

The province of Mantiqueira stretches from Uruguay to the south of Bahia (about 3000 km) along the Atlantic coast with a NNE-SSW orientation. Second (Heilbron et al. 2004), the province constitutes a complex unit, representing an orogenic system developed during the Neoproterozoic encompassing the orogens: Araçuaí, Ribeira, Brasília Meridional, Dom Feliciano, São Gabriel, with Bacia do Piratini located outside the Dom Feliciano orogen.

The coastal plain is made up of Cenozoic deposits developed on the crystalline basement. The constituent deposits are: alluvial deposits systems and Laguna-Barreira depositional systems I to IV. The Laguna-Barreira I deposits are the oldest, developed in the non-Pleistocene as a result of a first transgressive-regressive event, as well as the Laguna-Barreira II and III deposits that will follow. Laguna-Barreira IV is more current and developed in the Holocene due to recent post-glacial transgression (Tomazelli and Villwock 2005).

The Piratini Basin has an interesting variation in sediment dispersion in its different zones. Given the lithological characteristics of the crystalline basement, this area of the basin has low permeability. In this area we canais downstream to sculpt valleys and grooves due to the influence of the regional tectonics. This is also the highest relief zone of the basin, being composted by very shallow and stony soils (Telles 2002), without concentrating deposits.

The alluvial deposits are concentrated in the area of the coastal plain, which represents the sedimentary part of the downstream in the flatter areas. This zone is made up of very wet soils (hydromorphic soils), soils formed by sandy sediments and soils formed by silt and clay where the vegetation develops (Telles 2002).

RESULTS AND DISCUSSION

The code developed for simulating granulometric dispersion generates as a result a grid named grain type, not asc format that allows viewing two results using either Landlab, software or GIS (Geographic Information System) that supports this format. The results for dispersion in the Piratini Basin area varied with the chosen cell size (figure 4).

In the simulation using 90 m cells (figure 4a) the deposits in the current area are concentrated in the area corresponding to the part of the basin located in the coastal plain

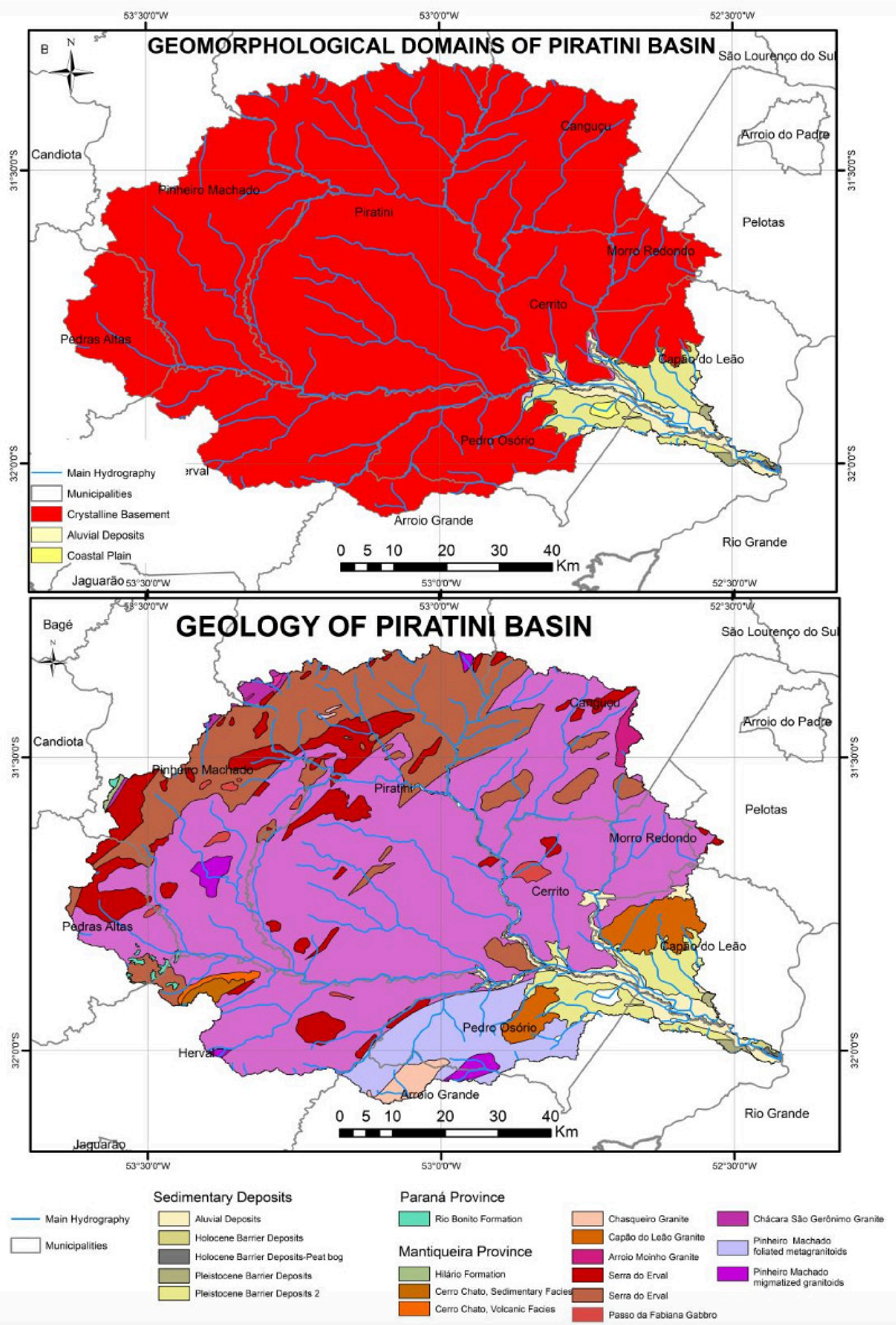
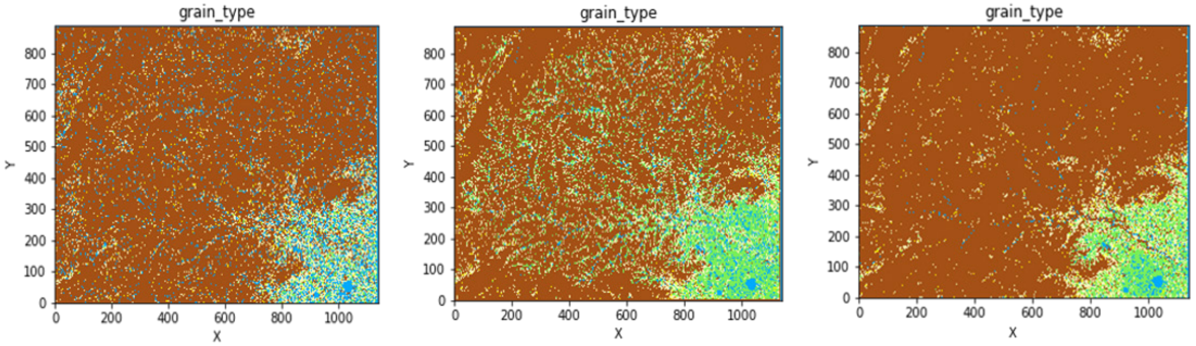
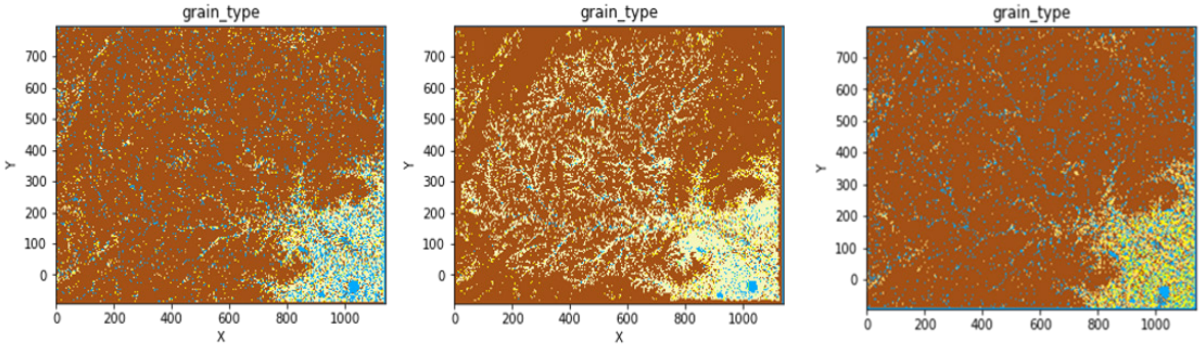


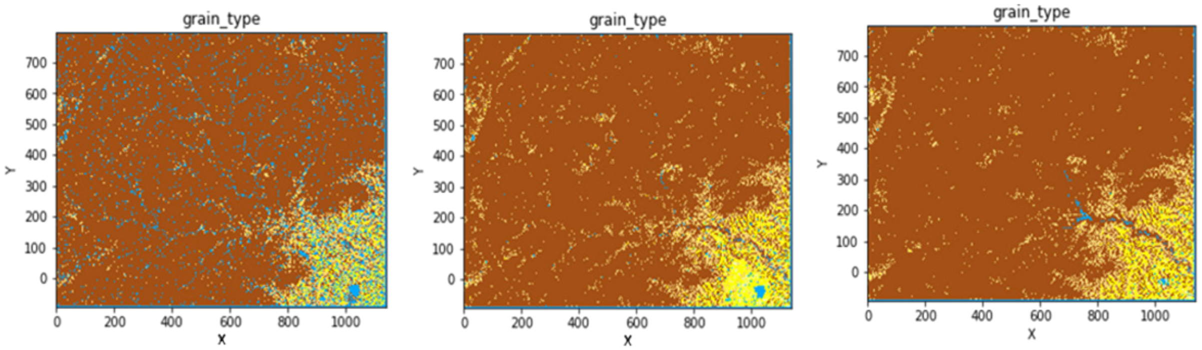
Figure 3--Map with the geomorphological domains of the Piratini Basin and the geological map of the Basin.



(a) current topography (b) topography in 10000 years (c) topography in 50000 years



(d) current topography (e) topography in 10000 years (f) topography in 50000 years



(g) current topography (h) topography in 10000 years (i) topography in 50000 years

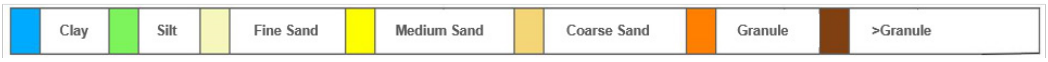


Figure 4- Result of the non-DEM dispersion simulation with cells of 90 m (figures (a), (b) and (c)), 180 m (figures (d), (e) and (f)) and 360 m (figures (g), (h) and (i)) using the current area and the simulated area as LEM for 10,000 and 50,000 years.

and where the alluvial deposits are deposited, with a heterogeneity in the distribution of grains, predominantly clay, silt and sand. fine.

Simulating the evolution of the terrain in 10,000 years (figure 4b), due to the evolution of the terrain and the excavation and smoothing of the simulated drainages as LEM, the formation of deposits in the tributaries of the basin is noted. A decrease in the amount of clay and an increase in the amount of silver-sized particles were observed. At evolution in 50,000 years (figure 4c) it exhibits concentrated deposits just at the outflow point of the basin. These are the deepest channels excavated in the topography, accumulating deposits only in the lowest and flattest area, corresponding to the coastal plain. Sediments of silt size, clay and fine sand predominate.

Using cells with a size of 180 m to simulate granulometric dispersion in the basin (figure 4d) we observe the same pattern in the distribution of two DEM deposits of cells of 90 m (figure 4a), but we can notice a variation in type of grain that predominates, predominantly depositing clay and fine sand.

With the evolution of the terrain over 10,000 years (figure 4e), fine sand deposits were delineated in the drainages of two basin tributaries, with fewer ramifications compared to a cell size of 90 m. In the region of the outflow from the basin predominate grains of fine sand size. In 50,000 years of evolution of the basin (figure 4f) the deposits were again concentrated only in the exutory region. Fine to medium sand predominates and a channel excavation with clay deposits in the central part is observed.

Using the DEM with 360 m cells, in the current area dispersion simulation (figure 4g) clay deposits predominate in the drainage tributaries. Not outflowing from the basin, a heterogeneous distribution of the size of grains was observed, there was little clay, while in the middle area and silent there was a greater quantity.

Over 10,000 years of evolution of the area (figure 4h) the formation of deposits in the drainage zone of the basin is not observed as smaller cell sizes (figures 4b and 4c), there is only a tendency to form deposits of medium area delineating the canais. The deposits predominate in the outflow region of the basin and the dominant grain is in the middle area, with clays deposited parallel to the main channel. In 50,000 years of evolution (figure 4i) the area with deposits is more restricted in relation to the observed same step of time with other cell sizes (figures 4a and 4g). The deposits are medium-sized grain deposits, a channel is excavated and clay is deposited in the central part of this.

Using different cell sizes in the DEM we observed different and subtle variations not resulting from the dispersion simulation. With the increase in the size of the cells, a decrease in the values of the grid of the Slope and an increase in the values of the grid of the drainage area were observed, which are important parameters used in the calculation of the grid size. This effect can be attributed to a loss of information with the resampling of two DEMs for larger cell sizes.

A tendency to increase the size of grains with larger cell sizes was noted, which can be attributed to the higher values observed for the drainage area and also to the elimination of noise and artefacts.

The application of the Critical Gradient was the delimiter of the zones where alluvial channels must be formed, or not, not a model. This function has the drainage area as the main parameter, which acquires higher values when a DEM with larger cell size is used, resulting in a slight decrease in the deposit areas, for the same pattern is maintained.

With the evolution of the area over time, a tendency to deposition of larger grains has been observed, which occurs as a consequence of the increase in the amplitude of variation of the Slope. This effect has also been observed in the topography, having an accentuation of the amplitude of variation from the highest areas to the lowest, being the area of drainage and the high areas part of the land that suffers the most erosion, and the area of exutório to part where or sediment is mostly deposited.

CONCLUSIONS

In this work, a granulometric dispersion model for fluvial environments was proposed to be used together with LEMs and implemented with the Landlab library. A case study of the Piratini Basin area was carried out using different cell sizes in the DEM of the area and the results of the simulation are consistent, the deposits are concentrated in the drainage and outflow areas of the basin where they are expected to be found. There are several variations in the results of the simulation when cells of different sizes are used, thus maintaining the same tendency and consistency in the deposition areas.

Using the LEM for evolution of the terrain or model simulated the deposits in areas where there was an increase of material and reduced the deposits in areas where there was erosion, or what is expected for fluvial deposits.

Proposals for the development of future work: a more in-depth case study, with field trips to delimit deposit areas; tests in a greater diversity of areas; A focused study did not effect the variation of two parameters for different cell sizes and topographies.

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