The riverBedDynamics v1.0 Model: A Landlab component for computing two-dimensional sediment transport and river bed evolution

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**Abstract.** Landscape evolution models (LEM) are generally composed of two coupled components, a flow hydraulics model that routes the water across a model landscape and a geomorphological model that modifies the terrain properties, like bed surface elevation. For simplicity, LEM used in long-term simulations over large watersheds often assume only river erosive processes, where sediment detached from the bed istransported (i.e., detachment-limited), and a generalized increase in bed surface elevation (i.e., tectonic lift). LEM currently available in the Landlab modeling platform were developed with this premise in mind. Therefore, they do not perform well in gravel-bedded rivers because they lack the capacity to simulate sediment deposition and track changes in the substrate stratigraphy patterns that arise as a response to the flow characteristics. Here, we developed, implemented, and tested riverBedDynamics, a new Landlab component to simulate the evolution of bed surface elevation and grain size distribution in large two-dimensional grids based on the Exner equation for sediment mass balance. To obtain the local shear stress and calculate bed load transport rates and grain sizes we extended the capabilities of OverlandFlow, a hydrodynamics flow solver, to include spatially variable roughness and rainfall inputs. Our proposed LEM correspond to the dynamic coupling of the modified version of OverlandFlow and riverBedDynamics. Comparison of our LEM to analytical and previously reported solutions show that it can accurately predict time-varying local changes in bed surface elevation, including erosion and deposition, and grain size distribution. Additionally, an application on a synthetic watershed illustrate how varying bed evolution and rainfall intensity can have different degrees of impact in flow discharge and bed surface elevation across the domain.

# 1 Introduction

LEM are a fundamental tool for geomorphologist because they allow one to predictterrain changes under different possible climate, management, or urban development scenarios (Coulthard, 2001). Currently available computational models usually differ in the number of different physical processes considered, the way they route water and sediment across a landscape, and how the domain and its features are represented when solving the governing equations (Coulthard, 2001; Pazzaglia, 2003; Temme et al., 2017). For instance, the GOLEM model (Tucker & Slingerland, 1994) assumes a steady single-flow-direction water discharge defined as the product of drainage area and rainfall rate. CAESAR (Coulthard et al., 2002) uses a routing scanning algorithm to define flow direction, allowing for multiple-flow-directions, thus avoiding single flow direction. In terms of defining a drainage network or small channels (relative to the cell size) within a catchment, different models have different approaches. This is important because a channel can potentially be smaller than the cell size and the not be explicitly included in the grid used to solve the governing equations. The CHILD model (Tucker et al., 2001) use an adaptive triangulated irregular mesh to better distinguish between channels and floodplains. In CAESAR, the cells must be concentrated near the channel to obtain more accurate results. Usually, the timescale in which a model can operate depends on the number of simplifications to the natural processes involved in the evolution of a landscape. More simplemodels can predict changes in the order of millennia in relatively small execution times, but they sacrifice accuracy and precision. Fine and detailed models, SedFoam (Cheng et al., 2017) for instance, can predict small scale events such as sand concentration at a submillimeter scale but are computationally expensive.

Most LEM assume that river erosive processes and tectonic lift are the controlling factors that shape a basin in the long-term (ref needed). Such assumptions seem to be more realistic in bedrock than in gravel-bedded rivers because detachment-limited (sediment detached from the bed will be transported) conditions exist (Campforts & Govers, 2015; Royden & Taylor Perron, 2013; Whipple & Tucker, 1999). The evolution of the shapes (i.e., longitudinal and cross-sectional profiles) and alignment of a river does not only respond to erosion and a generalized increase in bed surface elevation but also depends on the sediment that is deposited at different locations. For example, gravel-bedded rivers with local imbalance of mass flux can deposit sediment, thus they increase the slope and the capacity to transport material until a new equilibrium is reached. Adding the capability to predict deposition (in addition to erosion) to LEM as a mass conservation problem makes the model development more complicated because it requires an accurate representation not only of flow direction but also of velocity and depth. Also, it requires conducting a mass balance at individual cells or control volumes thus increasing the number of calculations per simulated time step.

Accurate LEM can be constructed using the components available in Landlab, a modeling platform written in Python the create, assemble, and run bidimensional (2D) models. Thanks to the plug-and-play capacities of Landlab different processes can be included by combining the adequate components. For example, Adams et al. (2017) used OverlandFlow coupled to DetachmentLtdErosion to analyze how incision across a watershed varies when using a more accurate flow routing method. However, DetachmentLtdErosion is not applicable to gravel-bedded rivers because it uses the stream power law which ignores the effects of fractional sediment transport and deposition. An alternative to include more detailed sediment transport processes is NetworkSedimentTransporter (Pfeiffer et al., 2020), a lagrangian model that predict changes in bed material grain size and river bed elevation based on bed load estimates through a river network. It can potentially be used in long-term simulations and is very accurate in its predictions, but it was not designed to predict bed surface changes at every location within a watershed. Given the potential of OverlandFlow to predict with high accuracy the flow hydraulics under non-steady and non-uniform flow conditions, and that there is no available component in Landlab to accurately represent the dynamics of sediment transport in gravel-bedded rivers in a 2D distributed way, we proposed, developed, and tested a new component, riverBedDynamics, that addresses this knowledge gap.

riverBedDynamics was designed to work in gravel-bedded rivers. Four bed load transport models are available, covering the requirements of simple bed surface elevation predictions, using Meyer-Peter & Müller (1948) equation, or more advanced fractional sediment transport to simulate bed surface elevation and grain size distribution evolution and changes in the stratigraphy using Wilcock & Crowe (2003) model. All sediment transport predictions are based on the unsteady total shear stress, which accounts for spatial and time gradient in flow velocity and local variations in bed elevation and water depth. Our component was coupled to an extended version of OverlandFlow, from which all hydraulics variables required to calculate the total shear stress are obtained. Evaluations of our component are conducted using test cases with analytical solutions from previously reported models. An application to a large watershed is used to explore large scale applications of the component.

# 2 A general overview of the Landlab modeling approach

Landlab is a Python-based interdisciplinary open-source platform containing a series of libraries and tools that allows people to use, explore, and develop computational landscape models related to earth surface dynamic processes (Barnhart et al., 2020; Hobley et al., 2017). The general structure of Landlab has been described in detail in several studies (e.g., Adams et al., 2017; Barnhart et al., 2019, 2020; Hobley et al., 2017; Shobe et al., 2017; Tucker et al., 2022), therefore, we only focus on the main aspects related to the implementation of the riverBedDynamics component within our modeling approach. Landlab’s Gridding Library is the core of our new component. Data creation, manipulation, and exchange between different components is based on a 2D structured grid (irregular grids are not currently supported by our component) which can handle numerical operations for flow, bed surface, and sediment variables at a given simulation time (e.g., topographic gradients, sediment mass balance, mapping velocity from grid links to nodes, etc.). The elements of the grid in which our component is built are nodes, cells, and links (Figure 1). Nodes are set of (x;y) points. Links are a line segment connecting neighbor nodes with a fixed directionality. For instance, links are always pointing towards the right and north for the increasing x and y directions, respectively. However, this link ordering is only for grid representation and has no effect of fluxes direction which are defined when solving the governing equations of given processes. The area around a non-boundary (i.e., interior) node, bounded by a set of lines known as faces, are cells. In our component all cells are rectangular-shaped and have the same dimensions in the x () and y () direction.

Diagram

Description automatically generated

Figure 1: Elements of a Landlab grid used by our component. An example of a portion of a grid of 5 by 5 nodes is shown here. Number inside the circles represent the identification (Id) of nodes and number next to arrows are links Id. Information is stores in nodes and links. For example, surface bed elevation is stored in nodes while gradient in links.

We developed our component around the RasterModelGrid class because it allowed us implementing the numerical solution of partial differential equations (e.g., Exner equation for sediment mass conservation) and spatially variable processes in a relatively simple and direct representation. For example, the bed load transport equation of Meyer-Peter & Müller (1948):

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 1 |
|  |  | Eq. 2 |

where is the dimensionless critical shear stress, is the dimensionless volumetric bed load transport rate per unit width, and is the dimensionless shear stress, is encoded as:

*tauCrStar = 0.047*

*qbStar = np.where(tauStar-tauCrStar>0 , 8 \* np.abs(tauStar-tauCrStar)\*\*(3/2) , 0)*

where np denotes the use of Numpy, the Python library for numerical computing, and the variable *tauStar* is read from the grid. The mathematical structure in Landlab closely resembles the form of Eq. 1 and Eq. 2 and allows building a bed load transport model applied for the whole domain without iterating over grid indices.

Data exchange between different components is also handled by the grid. For example, after calculating , we could pass the bed load fluxes predictions to another component or function to estimate the sediment mass balance in all cells. The volumetric bed load transport rate per unit width (when using Eq. 2) is:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 3 |

where , and are the sediment and water densities, is the acceleration due to the gravity, and is the median size of the sediment grain size distribution (GSD). In Landlab can be stored in a grid link using:

*grid[‘link’]['sediment\_transport\_\_bedloadRate'] = qbStar \* (np.sqrt(R\* g\*D50) \* D50) \** *np.sign(tau)*

and can be accessed or even modified by another function or component. Some “*self*” instances were dropped for clarity. The last term, *np.sign(tau)*, represents the shear stress field and it gives the flux the appropriate direction.

Boundary conditions in our component are intrinsically linked to those specified in the OverlandFlow component (Adams et al., 2017). Nodes that have been defined as “boundary” in Overlandflow can be specified as open, fixed gradient, or closed (no flux) boundary. By doing so, it defines how surface water flow behaves in those nodes and consequently our component does not require a re-definition of boundary conditions and will calculate sediments fluxes according to the local flow conditions. The only exception is at the domain outlet, where riverBedDynamics requires the specification of the fixed bed surface elevation or a zero-gradient (for more details see section 3.4).

# 3 Model description

Our component was designed to be coupled to a flow solver such that continuous feedback between surface flow and riverbed properties determines the behavior of the system. In our case, we developed all routines using OverlandFlow (Figure 2), but any flow solver can be used thanks to the “plug-and-play” capabilities of Landlab. At all time steps, flow governing equations are solved at each location across the whole domain by OverlandFlow, which obtains flow depth, velocity, and stream discharge. The routines of riverBedDynamics can be conceptualized in two major parts: i) bed load transport and ii) riverbed evolution. In the first part, riverBedDynamics takes the surface flow variables,which are stored in the grid, and calculates the bed surface grain size properties, local shear stress, and bed load transport rate. In the second part, net sediment fluxes in each cell are calculated and the bed surface elevation and bed properties like bed grain size distribution are updated at each cell, completing the cycle at each time step.

Graphical user interface, diagram

Description automatically generated with medium confidence

Figure 2: Simplified workflow for the coupled OverlandFlow and riverBedDynamics routine. The driver file is a procedure script containing the set of instructions to create all the required data and loop through time dynamically linking and updating surface flow and river sediment variables.

## 3.1 Modifications to OverlandFlow V1.0

The original version of OverlandFlow (Adams et al., 2017)) was extended to include some attributes that made implementing the coupling between flow and sediment variables easier and more representative of spatially variable environment at a watershed scale. We did not modify the actual flow solver (i.e., the algorithm of de Almeida et al. 2012). Instead, we added or modify some functionalities to this new version that we named OverlandFlowSpatiallyVariableInputs. Given that to core of this new component is in essence the same than that of Adams et al. (2017) in this article we refer to the flow solver simply as OverlandFlow unless a clear distinction is required for scripting purposes.

The new functionalities include a spatially variable roughness attribute (grid field *'bed\_surface\_\_roughness'*). In the original version a single roughness coefficient, in the form of Manning’s , was specified in the whole domain. Given that floodplains and river beds rarely have the same roughness (Arcement & Schneider, 1989; Barnes, 1967) we implemented a method that allows specifying different surface roughness at any location. Bed surface roughness can be assigned to nodes using the same methods that when assigning bed elevation. For example, the user can read in gridded data from an ASCII file in Esri ArcGIS format or directly create/edit the field *'bed\_surface\_\_roughness'* to fill it with the required values. With this implementation a modeled river can contain different roughness in the headwaters compared to low-slope regions making it relatively more realistic. Notice that although specifying roughness at individual cells is now a mandatory variable, the user can still specify a uniform roughness coefficient by simple assigning the same value to all nodes and the model behaves like the original version.

A second modification includes the implementation of a spatially variable rainfall intensity within the watershed. In the original version rainfall intensity was uniformly distributed across the domain at a given time. Consequently, flow discharge is consistently increasing in the downstream direction of the river path due to continuous inputs of water from rainfall. One advantage when using our modification compared to the original version is that in large watersheds a storm can be better represented in the region where precipitation occurs, leaving dry zones to stay dry during the simulation. Thus, water can come exclusively from headwaters or a user defined region. Also, it allows developing more uniform flow conditions because consecutive cells (in the sense of downstream flow path) can have the same discharge at a given time. Like in the roughness modification, in this new version rainfall intensity is specified by the user at individual nodes.

We also extended the functionality of the adaptive time step calculator function. Now the user can define a time step and during run-time OverlandFlow will select the minimum between this user-defined value and the one calculated by the de Almeida et al. (2012) algorithm (already implemented in OverlandFlow). We added this functionality to partially control the effects that produce a change in bed surface elevation in the flow surface variables which in turn affect local CFL (Courant–Friedrichs–Lewy condition) and therefore the stability of a simulation. By adding this functionality, we ensure that always the flow’s CFL is less than the alpha value defined when instantiating OverlandFlow (default 0.7).

## 3.2 Flow variables and shear stress calculations

For each time step during a simulation OverlandFlow will solve the 2D flow equations at all grid links to obtain the surface water discharge per unit width () and water depth (). Water depth at nodes is then calculated based on mass conservation considering all flow moving in and out of a given node. Flow velocity is not directly obtained but can be calculated at links according to with velocity components for the east–west links (or x direction, for example link 19 in Figure 1) and for the north-south links (or y direction, for example link 24 in Figure 1). Our sediment transport rate calculations are based on the local shear stress considering an unsteady friction slope (Ghimire & Deng, 2011) according to:

|  |  |  |  |
| --- | --- | --- | --- |
|  | and |  | Eq. 4 |

where and are the friction slopes evaluated on the x or y direction, respectively, is the bed surface elevation, and is time.

Each individual term in Eq. 4 is calculated directly using the structure,ID numbering and connecting neighboring information, and built-in methods of the LandLab grids. Topographic gradients ( and ) are based on the bed elevation slope at nodes defining a link using the *calc\_grad\_at\_link* method. The same approach was used for water depth spatial gradients ( and ). Velocity spatial gradients are approximated using a central difference scheme according to:

|  |  |  |  |
| --- | --- | --- | --- |
|  | and |  | Eq. 5 |

where subscripts , ,, and indicate the location of the link considered, in this case at the right and left of the link where the gradient is being estimated (Figure 3). Velocity time gradients are approximated using the backward Euler method defined as:

|  |  |  |  |
| --- | --- | --- | --- |
|  | and |  | Eq. 6 |

where is the time step and the subscripts and indicate the current and previous time steps. Velocities at these time steps are stored as a data field in the grid by our modified OverlandFlow component (other time steps are continuously overwritten).

Diagram

Description automatically generated

Figure 3: A representation of the stencil used to calculate the velocity gradient at links. Cells are separated only to highlight the definition of velocities at links. The gradient at the location of the link with velocity is estimated using a central difference scheme and considers the neighboring links. The same principle applies to calculate but are not represented in this figure.

The local shear stress at each link is then calculated according to:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 7 |

Usually, the shear stress is defined using the hydraulics ratio instead of water depth to include the effects of roughness with the channel sides. When modelling hydraulics flow this effect is critical if the cross section of a river is well captured by a single cell because a large proportion of flow surface is in contact with the riverbed (i.e., bottom and sides of a cross section). When a cross section is defined by more cells, most of cell sides are in contact only with water, so bank roughness becomes less important, and the hydraulics ratio can be simplified as . Given that is difficult to anticipate if the section of a river will be well represented by a single or multiple cells we set as default the option of using in the shear stress definition. Nevertheless, the user can override this and obtain the shear stress as:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 8 |

where is the hydraulics radius, is the wetted area, and is the wetted perimeter. For north-south links we have and . To activate this option set *useHydraulicsRadiusInShearStress = True* when instantiating the riverBedDynamics component.

## 3.3 Bed surface properties and sediment fluxes calculations

Before calculating sediment fluxes riverBedDynamics defines the bed properties that are used in the bed load transport equations. Like in the implementation of spatial roughness in the modified version of OverlandFlow, grain size distribution (GSD) can vary spatially and is therefore specified at different nodes. In the raster file or NumPy array the location of different GSD is defined at each node using an identification number that is linked to a cvs file,or any other files used for storing data in tabular format, containing the GSD of a given location. Grain sizes, defined as percentage passing, can range from fine sand to large boulders. Cohesive sediments are not supported by our component. The sizes corresponding to 0 and 100% must be always present in the definition files independently of which sediment transport model will be used. The purpose of this is to use the same input format independently of what equation is selected. Once the GSD has been loaded riverBedDynamics will calculate the sand fraction (), , the geometric mean size (), and the geometric standard deviation () at each node. These last two variables are defined following the method of Parker (1990). After bed properties are defined they are mapped into links assuming equal weights of the connecting nodes in the case they have different GSD. By allowing a spatially variable GSD some typical characteristics of a real watershed can be explicitly included. For instance, a GSD featuring coarser grains in headwater and finer fractions in lower gradient regions. Depending on the bed load equation selected these bed surface properties can be updated at each time (i.e., when selecting Parker, 1990 or Wilcock & Crowe, 2003) or remain constant throughout the whole simulation (i.e., when using Meyer-Peter & Müller, 1948 or Fernandez Luque & Van Beek, 1976).

Four different sediment transport equations are available in our component. These equations are described in detail in the original articles (Fernandez Luque & Van Beek, 1976; Meyer-Peter & Müller, 1948; Parker, 1990; Wilcock & Crowe, 2003) and used extensively in sediment transport studies (e.g., Barry et al., 2004; Schneider et al., 2015; Yager et al., 2007). Therefore, only the aspects related to their implementation are described here. Our first equation, that of Meyer-Peter & Müller (1948), was already presented in Eq. 2 but it is repeated here for convenience.

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 9 |

where is valid only when or else . The dimensionless shear stress is expressed as . For simplicity we dropped the and subscripts of Eq. 7 in this and following uses of .

Our second sediment transport equation is that of Fernandez Luque & Van Beek (1976) and is defined as:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 10 |

where and requires that otherwise . The volumetric bed load transport rate per unit width when using Eq. 9 or Eq. 10 is calculated using Eq. 3.

The effects of bed slope in critical shear stress (Lamb et al., 2008; Mao et al., 2008; Mueller et al., 2005; Yager et al., 2012) can be partially included in these two bed load transport models by setting the option *variableCriticalShearStress = True* during instantiation (by default is *False)*. When is optional capability is activated the equation of Mueller et al. (2005) is used to calculate according to:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 11 |

where is the topographic gradients defined as and for the and directions, respectively.

The third option is the surface-based bed load transport equation of Parker (1990) which includes the effects of sediment mixtures in gravel-bed rivers. In this case, if sand is present in the GSD the component will automatically remove it and renormalized the GSD curves to adjust for the change. The shear stress is here normalized using instead of as follows:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 12 |

The dimensionless measure of shear stress is:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 13 |

where is the reference Shields stress. To account for the effects of sediment mixtures a hiding function is used:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 14 |

the subscript denotes the ith grain-size class. The function is:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 15 |

where and are functions that are calculated automatically within the component. The dimensionless transport rate for each ith size class is defined as:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 16 |

and the function is:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 17 |

To obtain the fractional bed load in each ith size class () we used:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 18 |

where is the volume fraction of the ith grain-size class and the number of grain size classes with characteristic diameters .

The fourth bed load transport equation included in our component is that of Wilcock & Crowe (2003). Similar to Parker (1990) this model can handle sediment mixtures. However, in this case the effects of sand content are explicitly included in the reference Shields stress which is defined as:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 19 |

The dimensionless measure of shear stress is and the hiding function is expressed as:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 20 |

where the exponent is:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 21 |

The dimensionless transport rate for each ith size class () is:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 22 |

To obtain the fractional bed load in each ith size class () we used:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 23 |

The volumetric bed load transport rate per unit width for each grain size when using Parker (1990) or Wilcock & Crowe (2003) is calculated using:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 24 |

Given that we are working in a 2D structured grid we can assign directionality to depending on the link in which it is being calculated, for east–west and or for north-south links, and sense by multiplying Eq. 24 by the sign of . The total bed load transport rate per unit width is defined as the sum of the bed load transport rates of each grain size .

## 3.4 Sediment mass conservation and bed properties update

Once the sediment fluxes and bed load GSD at each link are calculated it is possible to conduct a mass balance at nodes and determine changes in bed surface elevation and bed GSD. Surface bed elevation changes are estimated by the riverBedDynamics routine using the Exner equation defined as:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 25 |

where is the bed porosity. The equation states that the change in bed elevation in time within a control volume, a cell in this case, is controlled by the sediment fluxes crossing the faces of a cell (Figure 4).

Diagram, schematic

Description automatically generated

Figure 4: Examples of an increasing (left) and decreasing (right) bed surface elevation in time. Sediment fluxes across cell faces determine the net bed load transport rate within a cell and consequently dictates erosion or deposition of sediment. Sediment transport rate per unit width magnitude is represented by the length of the arrow line. In the left, the sum of the three fluxes entering the cell is larger than that exiting, therefore, there is net accumulation of sediment, and the bed elevation increases. In the right, fluxes in the direction are equal in magnitude so they cancel each other, in the direction the flux leaving is larger, consequently the bed elevation will decrease.

We used an explicit method to approximate the solution of Eq. 25. The gradients in volumetric bed load transport rate per unit width in the and directions are:

|  |  |  |  |
| --- | --- | --- | --- |
|  | and |  | Eq. 26 |

where the locations , , , and are shown in Figure 4. The right-hand side of Eq. 25 can be expressed as:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 27 |

here, and are the volumetric bed load transport rates in each direction, is the net volumetric bed load transport rate, and is the area of a cell. Considering these definitions, the explicit solution to Eq. 25 is:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 28 |

Boundary conditions for updating the bed surface elevation are only required at the watershed outlet. Two options can be specified, zero-gradient, thedefault option, and a fixed-value condition. When other type of boundary conditions are required, like an elevation that changes in time following a given curve, it can be specified by setting individual nodes or links of the grid using Landlab boundary condition handling. Fixed-value conditions can be applied not only to the boundaries but also to internal nodes, so they can remain unaltered throughout the whole simulation. This optional capability is accessed by editing the field *'bed\_surface\_\_fixedElevation'.*

Sediment mass entering or leaving a cell not only can alter the bed surface elevation but also its GSD. We represent the evolution of the surface and subsurface GSD by means of three layers corresponding to the bed load, surface, and substrate layers. The bed load layer is the one defined by the bed material being transported close to the riverbed and calculated according to section 3.3. The surface layer, also known as active layer (Cui, 2007; Hu et al., 2014; Parker et al., 2000), can exchange material with the bed load or substrate layer depending if the bed aggrades or degrades, respectively. The substrate includes all the material below the surface. To account for the dynamics of surface grain sizes we implemented the grain size specific form of the Exner equation of Parker (1991).

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 29 |

where is the active layer thickness, estimated as ( is the 90th percentile of the bed surface GSD), and accounts for the interchange of sediment between the active layer and the substrate interface and correspond to the fraction of material in the ith grain size exchanged between these two layers. In our model we used the transfer function of Toro-Escobar et al. (1996):

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 30 |

This equation states that when the bed degrades the surface GSD is that of the substrate (Figure 5c) and when the bed aggrades the substrate starts to exchang material with the surface and bed load assuming a weighted average of theGSD).

We solved Eq. 29 explicitly approximating the derivatives as:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 31 |
|  |  | Eq. 32 |

the direction has an equivalent discretization (just replacing for ). The coefficient is used to switch from an upwind to central difference scheme. For stability purposes we opted for a default value of 1. The explicit solution to Eq. 29 is:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 33 |

For simplicity we dropped some subscripts, but all variables are evaluated at the current time step except for .

Given that our model can predict temporal changes in bed surface elevation and GSD we implemented stratigraphy tracking capabilities, thus allowing a better representation of processes that are not purely erosional and depositional. Our model records the current and past GSD and elevation of the surface and subsurface across the whole watershed (Figure 5). At the beginning of a simulation the surface and subsurface have, by default, the same GSD (Figure 5a). But, once deposition starts occurring new layers can be created and added to the subsurface if the user-specified vertical thickness (*newSurfaceLayerThickness*, default value of 1 m. in Figure 5b) is reached. In other words, at each timestep and at every location where the bed surface elevation increases by *newSurfaceLayerThickness* the model stores a new subsurface layer (Figure 5b). The GSD of new added layers is a time-averaged value of all the deposited surface layers registered between 0 and *newSurfaceLayerThickness* meters. Once a new layer is created it becomes the subsurface and is updated and used in Eq. 29 and Eq. 30 in the subsequent time step. In the case of eroding a newly created layer, the model reads the stored data and updates according to the elevation of the scoured layer (Figure 5d). When the bed surface is eroded below the initial bed surface elevation does not require any updates (Figure 5c). Given that this capability involves intensive writing and reading sequences we implemented the *nCyclesToProcessStratigraphy* option. So, writing stratigraphy data occurs only every *nCyclesToProcessStratigraphy* times the time step.

Graphical user interface, diagram

Description automatically generated

Figure 5: A graphical description of the model’s bed surface and subsurface GSD update algorithm. a) Definition of the bed surface elevation () at the beginning of the simulation (). b) A pure depositional process. The bed surface elevation monotonically increases, new subsurface layers are created every time the thickness of the deposited layer reaches , thus modifying the local stratigraphy. The deposited surface layer is calculated using Eq. 29. c) A pure erosional case. Bed surface elevation monotonically decreases, the surface and substrate have the GSD specified at . d) An alternating erosion/deposition case. A bed is eroded below the initial bed surface elevation (at ) after deposited new layers are eroded (at and ) and then sediment is deposited again (at ). The minimum local bed surface elevation is updated to and the GSD at is calculated using Eq. 29.

# 4 Running a model using the Landlab framework

Some general characteristics of the Landlab modeling approach were described in Section 2.0. Therefore, in this section we focus only on describing specific details of the variables, default configurations, unit system, and capabilities of our model. The component was designed to work exclusively using the International System of Units (SI). If imperial units are required at some point they must be converted into SI before using them as input. Gravitational acceleration is constant and equal to 9.80665 m/s2. During the instantiation of riverBedDynamics the user can select and define the values of (default 2,650 kg/m3), (default 1,000 kg/m3), bed load equation, (default value is 0.35), outlet boundary condition (*zeroGradient* or *fixedValue)*, the use of a slope dependent critical shear stress, and can deactivate the routines that compute bed evolution (setting *evolveBed = False*, by default is *True)*

When using our component, similar to all other Landlab simulations, a driver file is required. This file is a procedure script containing a set of instructions to import libraries, instantiate elements, load data, run and loop through time, and finalize a simulation. Once the elements have been initialized and are ready to loop in time, the two different basic routines that define our LEM are executed sequentially, first OverlandFlow then riverBedDynamics (Figure 2). When executing OverlandFlow, the only difference when working with our modified version (compared to the original one) is the specification of roughness and rainfall intensity in a spatially distributed format and setting a maximum time-step.

At every iteration within the time loop, OverlandFlow is executed and returns updated flow conditions (e.g., and ) across the domain and the required to predict changes in bed surface elevation and GSD (Eq. 28 and Eq. 29). Then, the first part of the riverBedDynamics routine calculates and stores a series of hydraulics and sediment transport variables. When selecting a bed load equation the following terminology is used: *MPM* for Meyer-Peter & Müller (1948), *FLvB* for Fernandez Luque & Van Beek (1976), *Parker1990* for Parker (1990), and *WilcockAndCrowe* for Wilcock & Crowe (2003). The default option is *MPM*. After all calculations are completed the second part of the riverBedDynamics routine starts and uses the calculated bed load transport rates per unit width and bed load GSD to modify the bed elevation and GSD according to the equations described in Section 3.4.

The results of all routines are stored as fields in the grid, but only the current time step is available for reading/writing, except for the velocity at the previous time step and stratigraphy properties. Therefore, when analyzing the changes of a given variable in time it must be stored in a local file in a user-defined format which is defined in the driver file. The format in which riverBedDynamics stores GSD results may be difficult to interpret because it was designed to be easily accessible by the component and not for user-readability. However, a postprocessing function called *formatGSDOutputs* is implemented and returns a pandas DataFrame which contains the GSD for each node or link, depending on the input, in a user-friendly format.

# 5 Verification and evaluation

## 5.1 Reproducing Adams et al. (2017) results using our modified OverlandFlow component

Our OverlandFlow version was tested using the analytical solution for wave propagation on a flat surface case as first presented by Adams et al. (2017) and originally developed by Bates et al. (2010) and Hunter et al. (2005). The idea of this test is to check if our version behaves in the same manner as the original OverlandFlow does under unsteady flow conditions. Our simulations were conducted in a flat domain of 6000 m long ( direction) and 800 m high ( direction) in which we used three different uniform grid configurations () with spacings of 5, 10, and 50 m. At the beginning of the simulation the domain was filled with a thin film of water of 1 mm. A uniform roughness coefficient was used (). Boundary conditions at the top, right, and bottom edges of the domain were set to closed. Flow enters through the left edge ( m) with a constant velocity of m/s and m/s and water depth changes in time according to . The analytical solution at any location and simulation time is:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 34 |

After 3600 s of simulation we obtained identical results to those presented by Adams et al. (2017), indicating that our modifications to OverlandFlow do not affect the core of the flow solver (Figure 6). A detailed validation is out of the scope our test and analysis but for more details on the validation the reader is referred to Adams et al. (2017).

Diagram

Description automatically generated

Figure 6: Water surface elevation predicted by the modified OverlandFlow component after 3600 s of simulation and the analytical solution. Different grid sizes were used to reproduce the results of Adams et al. (2017). The upper-right panel shows a zoom of the region delimited by the segmented red line.

## 5.2 Equilibrium bed surface slope in uniform flow conditions

To test the ability of our component for predicting changes in the bed surface elevation we obtained an analytical solution for an idealized channel with uniform flow conditions. In this case, a given bed load transport rate is imposed at the upstream boundary such that the bed surface slope must adjust until the channel reaches a stable condition. We combined Manning’s equation to include uniform flow conditions and Meyer-Peter & Müller (1948) to estimate bed load transport rate within the channel. By expanding Eq. 9 we can solve for the bed slope required to transport an imposed bed load rate ( in this case):

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 35 |

The equilibrium slope () is a function of which in turn depends on the flow discharge () and channel properties ( and channel width ) and it can be estimated (once the equilibrium state has been reached) by:

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 36 |

which is a form of Manning’s flow equation considering a rectangular channel (in our component all cells are rectangular-shaped) and shallow flows such that , therefore, . Combining Eq. 35 and Eq. 36 a solution for can be found.

|  |  |  |
| --- | --- | --- |
|  |  | Eq. 37 |

Note that Eq. 37 is valid only under uniform flow conditions and may perform poorly at intermediate bed states (i.e., when the bed is adjusting) because the flow is not uniform locally. This form of the analytical solution is convenient when using our LEM because, in terms of hydraulics variables, it only depends on and it can be specified as a boundary condition or using a rainfall intensity that generates the target .

We conducted two tests to evaluate the response of our component. Both cases start with the same initial bed configuration but differ in the imposed upstream sediment supply rate. In general terms, they consist of a 1500 m long, straight channel with an initial bed surface slope of 0.015 m/m, the elevation at the outlet is fixed at 0 m, and the surface roughness is = 0.03874. Flow discharge is constant = 100 m3/s and is specified by using a rainfall intensity of 0.01 m/s acting over a single cell of 100 m per side () located at the upstream boundary. The grid consists only of uniformly sized cells. The bed surface GSD is uniform with a grain size of 50 mm, the bed load transport equation is that of Meyer-Peter & Müller (1948). In OverlandFlow we specified *h\_init*, the initial water depth in all cells, as 1 mm, the time step is limited to a maximum of 5 s and left all the other variables with their default value. To better manage the interaction of boundary conditions between OverlandFlow and riverBedDynamics we added ghost nodes, one at the downstream and two and the upstream end. These ghost nodes are used to extend the study reach and help reaching uniform flow conditions once a new stable slope has been reached. The modeled scenarios are a purely aggradation case in which = 0.0087 m2/s and purely degradation case where = 0.0012 m2/s. By applying Eq. 37, the equilibrium slope for both scenarios are 0.025 and 0.010, respectively.

We run each case for 120 days and compared the predicted and analytical bed slopes in both cases at the end of the simulation. We chose 120 days as comparing point because the rate at which the bed elevations were changing were relatively small. Considering the changes in the last 10 days of simulation the aggradation case had an increase of 9·10-5 m/day and the degradation case a decrease of 4·10-4 m/day. We considered these rates small enough to be representative of an equilibrium condition.

In the aggradation case our LEM predicts an equal to 0.0251 (percentage error of 0.32 %), the degradation case had an of 0.0101 (percentage error of 1.439 %). Locally, the major differences between the predicted and analytical bed elevation are found in the upstream region, near where the sediment supply is imposed. The maximum local differences are 0.136 m for the aggradation case and 0.200 m for the degradation scenario (Figure 7). The small percentage error and how the general tendency of the local surface elevation (Figure 7) suggest that our component is able to accurately predict changes in bed elevation.

Chart

Description automatically generated

Figure 7: Changes in bed surface elevation for a case of a) pure aggradation and b) pure degradation. The analytical solution corresponds to the equilibrium slope given by Eq. 37. Only one point or elevation per cell was used for plotting. The small differences in bed elevation after 40 and 120 days indicate that the systems are achieving an equilibrium state.

We analyzed the sensitivity of our results to the mesh size in the pure aggradation case by comparing the bed elevation after 120 days of simulation using meshes with half and a quarter of the size of the beforementioned case (Figure 8). By the end of the run the average slope was 0.0251 in all cases. The percentage error was 0.32, 0.31, and 0.29 % for the 25, 50, and 100 m grid resolution, respectively. Beside the mesh size, the configuration was identical in all cases except for the maximum time step, which was 5 s for the 100 and 50 m cases and 2.5 s for the 25 m run.

Chart, bar chart

Description automatically generated

Figure 8: Sensitivity of the predicted bed elevation to the grid resolution after 120 days of simulation. Three different meshes were used and compared to the analytical solution.

## 5.3 Comparing bed load transport models predictions

We checked the predictions of bed surface elevation and local GSD for all bed load transport models included in our component using a test like the one described in the previous section. In this case, we used a 1500 m long, straight channel with an initial bed surface slope of 0.015 m/m, a fixed elevation of 0m at the channel outlet, a surface roughness of = 0.0275, a flow discharge = 100 m3/s specified by using a rainfall intensity of 0.02 m/s acting over a two cells of 50 m per side () located at the upstream boundary. The initial bed surface GSD has a of 32 mm and of 28.84 mm including grains ranging from 2 to 256 mm (Figure 9 d). The initial water depth (*h\_init)* at all cells is 1 mm, the time step is fixed and equal to 5 s. All other variables had their default value. The upstream sediment supply is = 0.0075 m2/s with the same GSD as the bed surface. The total simulation time was 120 days for all the models we ran. We choose this test configuration because our predictions using the bed load equations of Parker (1990) and Wilcock & Crowe (2003) can be verified using the algorithm developed and implemented by Parker (2004) RTe-bookAgDegNormGravMixPW.xls (Sediment transport morphodynamics with applications to rivers and turbidity currents, http://hydrolab.illinois.edu/people/parkerg/morphodynamics\_e-book.htm). Also, an analytical solution for Meyer-Peter & Müller (1948) can be obtained using Eq. 33. In the case of Fernandez Luque & Van Beek (1976), Eq. 33 can be modified using and replacing the constant 8 by 5.7 to obtain an equilibrium slope too.

We compared the predicted bed elevation of all bed load transport models at different simulation times (Figure 9 a and b). After 10 days the equations of Parker (1990) and Wilcock & Crowe (2003) predict a bed elevation with an upward-concave longitudinal profile and a higher elevation at the upstream boundary compared to the models that do not account for the whole GSD (Figure 9 a). Compared to the models implemented in RTe-bookAgDegNormGravMixPW.xls (hereinafter, Parker-ebook), predictions of riverBedDynamics follow all trends in the longitudinal bed elevation profile and forecast a higher elevation for Wilcock & Crowe (2003) than for Parker (1990) as it is seen in the Parker-ebook. The models of Meyer-Peter & Müller (1948) and Fernandez Luque & Van Beek (1976) have a more uniform slope along the longitudinal distance. There is no analytical solution after 10 days for these two models because the equilibrium condition has not been reached yet. After 120 days all models can be considered in relatively stable conditions based on the elevation rate of change at the upstream boundary node (0.15 m/day for Wilcock & Crowe (2003) and less than 0.6 mm/day for all other models). In all cases the longitudinal profiles show a relatively uniform slope (Figure 9 b). However, the magnitude of local elevation is different in all the tested models. The equation of Wilcock & Crowe (2003) predicted a steeper bed slope (0.0624 m/m), more than double than Meyer-Peter & Müller (1948) (0.0249 m/m) and Fernandez Luque & Van Beek (1976) (0.0311 m/m). Parker (1990) predicts an average bed slope of 0.0407 m/m. In general, predictions of riverBedDynamics using the model of Wilcock & Crowe (2003) are in good agreement with those predicted in Parker-ebook, but are slightly underpredicted (max difference of 3.4 m at the most upstream node) when using Parker (1990). However, these differences are only referential because we did not try to calibrate the models in Parker-ebook and only used an estimate of the coefficient in Manning-Strickler resistance relation (). The elevation predicted by the models of Meyer-Peter & Müller (1948) (0.0249 m/m) and Fernandez Luque & Van Beek (1976) are in good agreement to those calculated using the equilibrium slope (Eq. 33, errors below 0.23%)

We also analyzed the dynamics of bed surface GSD in terms of the evolution of the surface which we evaluated locally at different time during the simulation. In general terms, the bed quickly adjusted itself at the most upstream node (Figure 9 c, 1 day panel) with an increase in from 28.84 to 33.19 mm which then remains almost constant until the end of the simulation (final is 33.45 mm). Approximately during the first 9 days of simulation, the bed also experiences a local fining compared to the initial (i.e., have local lower than 28.84 mm), but after 10 days and until the end of the simulation the bed has a larger than 28.84 mm everywhere. On the 60th day of simulation the is practically the same in the whole domain (33.4 mm at and average of 33.3 mm), while the downstream end is varying at a rate of 0.008 mm/day. To complement our analysis we further compared the predictions in two cases: i) updating the substrate GSD (stratigraphy update in Figure 9 c, *newSurfaceLayerThickness* equal to 1 m) and ii) keeping the initial substrate constant during the whole simulation (no stratigraphy update in Figure 9 c). We observed that for this purely aggradation case updating the substrate GSD has little effect on the surface (notice that solid line overlaps with the cross symbol in Figure 9 c). To check if our predictions are correct, we compared them to those of Parker-ebook and found that beside relatively small local differences (max of 1.04 mm on day 5) thee magnitude and trends are match reasonable well. The observed differences in , although relatively small, can be attributed to the way in which flow is calculated. In our LEM we used the results of OverlandFlow, a 2D flow solver, that accounts for the unsteadiness of the flow while in Parker-ebook the flow is predicted using simplified relations for hydraulic resistance and the normal flow (local equilibrium) approximation. Still, as mentioned earlier, is not our intention to obtain the same result than Parker-ebook but rather to have a good comparison point and validate our results.

Although in this test case changes in substrate GSD do not affect the evolution of bed surface elevation and GSD we still analyzed the stratigraphy tracking capabilities of riverBedDynamics. In this case we analyzed a single location located at = 1000 m. Contrary to the surface GSD, the substrate only increased in . This is because by the time the first new layer was created (8.1 days) the GSD of the deposited layer at = 1000 m was on average coarser than the initial GSD (Figure 9 d). A total of 12 layers were created during the 120 days of simulations, the last one after 93.9 days. Ten of these layers were added before 50 days and seven before 30 days, indicating that most of the substrate GSD updated occurred during the first quarter of simulation (Figure 9 d subplot), where the bed conditions were more different than those observed in equilibrium conditions.

Chart

Description automatically generated

Figure 9: Changes in bed surface elevation and local GSD for all bed load transport models included in riverBedDynamics. Predicted longitudinal bed surface profile after a) 10 and b) 120 days of simulation. c) Changes in space and time of bed surface . Initial values correspond to those at the beginning of the simulation and are repeated in every panel for magnitude reference. No stratigraphy update correspond to the case in which substrate GSD is constant during the whole simulation and Stratigraphy update varies the substrate GSD depending on the parameters used in the simulation. d) Changes in substrate GSD at different simulation times for the node located at = 1000 m. Time changes in surface and substrate are shown in the subplot. The location of individual circle markers indicates the time when a new layer was formed and the substrate GSD updated. Filled circles correspond to those times shown in the GSD curves.

## 5.4 Application to a large watershed – Effect of rainfall intensity on morphological changes

All our previous bed evolution tests had a predominant flow direction and were restricted to pure erosion or deposition. We conducted a final test of our LEM in a more complex and larger watershed to analyze the how flow discharge and bed surface elevation varies at different locations within the domain under different rainfall events. We used the synthetic square watershed from Adams et al. (2017) which has an area of 36 km2 with a resolution of 30 x 30 m per pixel and elevations ranging from 0 m at the basin outlet to 225 m at the highest point (Figure 10 a). Two cases of temporal distribution of rainfall intensity were considered, both having the same total volume of water precipitated (10 mm). We referred to these cases as i) uniform, in which the rainfall intensity was 5 mm/hr lasting for two hours and ii) intermittent, where rainfall can reach up to 25 mm/hr during 350 s and then goes back to zero (Figure 10 b). Changes in flow discharge and bed surface elevation were quantified in three locations: Site 1 which coincides with the watershed outlet, Site 2 located upstream the outlet and upstream the confluence of the most downstream tributaries, and Site 3 located approximately at the center of the watershed (Figure 10 a).

We ran each model for 24 hours, set Manning’s n constant in the whole watershed with a value of 0.035, set the option for  *steep\_slopes* to *True* in OverlandFlow, used the bed load transport equation of Meyer-Peter & Müller (1948) with a of 32 mm, and allowed the critical shear stress to vary spatially using the equation of Mueller et al. (2005) (*variableCriticalShearStress* = True). All other variables during the instantiation of the components had default values. Each rainfall intensity case was simulated with and without activating riverBedDynamics (4 cases in total) to analyze the effect that the selected temporal distribution of rainfall intensity has on flow hydraulics (e.g., flow discharge) and in turn on morphological changes. When running only OverlandFlow (i.e., riverBedDynamics deactivated) the resulting hydrograph for both the uniform and intermittent cases have a relatively smooth shape at the three sites (Figure 10 b). In the intermittent case, the peak discharge arrives first at every site and has a larger magnitude (50.9 m3/s arriving after 2.1 hours compared to 42.8 m3/s at 2.6 hours for the uniform case). If the bed surface elevation evolves as a function of the local flow conditions (i.e., riverBedDynamics is activated) the resulting hydrograph had a lower peak discharge. At the outlet and at Site 2 the reductions are nearly 15% and 33% for the uniform and intermittent case, respectively (Figure 10 b). At Site 3 the changes in hydrograph shape are relatively small with discharge peak decreasing from 14.7 to 14.2 m3/s in the uniform case and from 20.3 to 18.9 m3/s in the intermittent scenario. Additionally, the shape of the hydrograph at sites 1 and 2 is no longer smooth everywhere and contains a small spike at the location of the highest discharge. In general, the rising and falling hydrograph limbs in both rainfall scenarios and in all sites are similar and the curves practically overlap each other. The largest differences in magnitude are concentrated around the peak discharge. To better understand how bed evolution affects flow dynamics we integrated the hydrographs in time and obtained the cumulative flow volume (subpanel cumulative flow volume, Figure 10 b). When considering the no bed evolution case, approximately after one day of simulation the flow exiting the watershed (sampled at the outlet) is equal to the volume of water that entered as precipitation (36·104 m3). This proves that mass is well preserved in OverlandFlow and that the square watershed has no sinkholes. However, a difference of 19.4·103 and 48.6·103 m3 between thepredicted cumulative flow volume and total rainfall is observed in the uniform and intermittent cases, respectively, when we let the bed evolve. This is not a mass conservation problem but rather a consequence of erosion and deposition patterns within the basin. In the selected sites riverBedDynamics predicts only deposition of sediment, except for Site 3 in the uniform rainfall intensity where the change is practically null. For these places, the intermittent scenario generates consistently larger depositions compared to the uniform case. Most of the bed elevation changes occurred during the first 3 hours of simulation, where the larger discharges and therefore larger shear stresses occurred. In other locations within the watershed we observed scour and deposition of sediments (Figure 11 a and b).

Diagram

Description automatically generated

Figure 10: Discharge and bed surface elevation response to different rainfall intensity scenarios. a) Synthetic square test basin. Three different sites, called Site 1, 2, and 3, were chosen for representing some of the spatial variability within the watershed. b) Hyetograph and hydrograph for the uniform (upper main panel) and intermittent (lower main panel) rainfall intensity cases. Subpanels represent the cumulative flow volume (in 103 m3) and change in bed surface elevation at the three selected sites.

The differences between the predicted cumulative flow volume and total rainfall after 24 hours of simulations can be explained by the morphological changes within the watershed. Here, we analyzed in more detail the intermittent case, but the same analysis is valid for the uniform scenario. When we let the bed evolve different patterns of erosion and deposition were created in the basin (Figure 11 a). In the intermittent case bed surface elevation changes ranged approximately between -2 to 2 m (±1.25 m in the uniform case). This combination of local scour and deposition affected the local flow and created zones that retained large volumes of water (Figure 11 b and c) in quantities practically equal to the volume differences (48.6·103 m3 for the intermittent case). They are not equal because after 24 hours the discharge flowing at the outlet is still 0.052 m3/s and reaches zero at around 36 hours. Most of the nodes where erosion or deposition was predicted are located close to confluences or regions where there are changes in the local channel streamwise direction. The total area that had erosion or deposition larger than 1 cm is 0.2907 km2.

PowerPoint

Description automatically generated

Figure 11: Local surface bed elevation variability and water depth after 24 hours of simulation. The watershed is represented using a grey scale to highlight the local area (nodes) where scour/deposition occurred and water was retained. a) A general view of the watershed indicating the three sampling sites for reference and nodes colored by bed elevation change. Given the basin size and scale we centered our analysis in the red-colored region, which is zoomed in in the following figures. b) Variation in surface bed elevation in the region near the outlet. c) Water depth accumulated at the represented region after one day of simulation.

# 5 Discussion

The results described in section 4 confirm that riverBedDynamics can be coupled with a surface hydraulics flow solver, OverlandFlow in this case, to predict the evolution of bed surface properties at a watershed scale. This first version allows us to simulate bed changes at different degrees of complexities. For example, when using the bed load transport equation of Meyer-Peter & Müller (1948) only bed elevation can be considered. But, when selecting the equations of Parker (1990) or Wilcock & Crowe (2003) changes in surface and subsurface bed elevation and GSD can be tracked in time. Thus, our LEM allows users to include or exclude certain processes depending on the specific prediction requirements. Our new component was developed using OverlandFlow but any flow solver available in Landlab can be used given the standardized components structure. For example, in very large watersheds, where local details are not as important as regional changes, the KinwaveOverlandFlowModel could be used with the consequent reduction of time simulations. If small scale information is required the OverlandFlow version of Adams et al. (2017) or the one modified by us may be required. Also, it could be possible that the assumptions, like negligible contributions from the advection term of the shallow water equations(Bates et al., 2010; de Almeida et al., 2012), included in the core flow solver of Adams et al. (2017) may not be representative in a complex fluvial system and a new flow model needs to be developed. In any case, the structure of riverBedDynamics and any other Landlab component will allow an easy model integration.

Our solution to the Exner equation, used to predict changes in bed surface elevation, is one of the simplest formulations when working in a 2D approach (for a detailed discussion see Furbish et al., 2017). Other more generalized forms of sediment mass balance have been developed and applied (Juez et al., 2016; Paola & Voller, 2005; Parker et al., 2000), but, we opted for a computationally efficient implementation that can be applied to a large watershed. In our formulation we assumed that rectangular elements could define the alignment of a channel. However, this may not be representative of channels with an important degree of curvature. A curvature coefficient similar to that implemented by Van De Wiel et al. (2007) could lead to more accurate results, especially near the confluences. In all our test cases we used channels without macro-roughness elements such as large boulders, vegetation, or any type of flow obstructions that can significantly alter the flow direction. Although our intention was to make riverBedDynamics as general as possible, we have not evaluated how the model behaves when is subject to sharp local gradients in shear stress induced, for example, by an obstacle. In this first version we implemented a slope-dependent critical shear stress equation (Mueller et al., 2005), which can be used in the models of Meyer-Peter & Müller (1948) and Fernandez Luque & Van Beek (1976). However, the original values are a result of data fitting, in the way it is implemented in riverBedDynamics, and must be used with caution because they do not correspond to the observed data from which they were derived. We included this capability based on previous evaluations (not presented in this article) where we noticed that some areas, especially riverbanks, where eroding at a faster pace than what they should, leading to artificial channel widening. Some sediment transport phenomena are not included in this first release. For instance, riverBedDynamics does not include suspended sediment motion or its effects in bed evolution. Also, sharp unnatural angles within the river bed can result because the effects of the angle of repose (sometimes called avalanche or sediment slide models) are not include in our component (Sanchez & Wu, 2011; Song et al., 2020). Lastly, we did not include the effects of sediment or particle diffusion (Furbish, Fathel, Schmeeckle, et al., 2017) which may smooth the bed profile making it more realistic (compared to large angles).

Riverbed Dynamics is the only component in Landlab that can predict sediment deposition in gravel bed rivers, all other components can only deal with transported-limited or detached-limited river erosion cases. This is done by solving a more mechanistic approach, particularly sediment mass conservation (Exner’s equation). However, one adverse consequence is that simulations can take up to 1.5 times longer than the DetachmentLtdErosion component (using the simplest configuration such as MPM, no stratigraphy tracking, and constant GSD) which may constrain the total simulation time. There is nothing that can intrinsically limit the simulation time in riverBedDynamics, but this mechanistic approach may be better suited for relatively small-time scale processes. We conducted a 100-year test simulation with no problem.

Our coupled OverlandFlow-riverBedDynamics approach in our LEM is in reality a decoupled way to solve for the evolution of a riverbed (see Cao et al., 2002; Colombini & Stocchino, 2005 for coupled and decoupled definitions and applications). This means that the governing equations are solved separately and the flow is “paused” while the component solves the Exner equation during a given time step (Figure 12 a and b). This implies that the selected time-step must ensure relatively small bed elevation changes to maintain the simulation stability. When working with flow, rainfall, and watershed conditions that generate dramatic elevation changes an optional local correction can be used to preserve the numerical stability and ensure mass conservation (Figure 12 c). Given that only the water surface elevation is affected after a change in bed surface elevation (water depth and discharge are not affected) it is possible to locally correct the water depth by running OverlandFlow for a few internal cycles and obtain a better water surface elevation around the nodes that had bed surface elevation changes (only those sharing links can be corrected). Once the internal cycle finishes, the corrected water depth is mapped into the grid. In this correction flow discharge is not altered and the values previously calculated are used whilelocal velocity is modified. This capability is configured in the driver file and an example of its use is given in the examples code for the test case used in section 5.4.

Chart, histogram

Description automatically generated

Figure : An example of the local water depth correction. An optional capability in riverBedDynamics, an erosional case is shown here but works for deposition as well. a) Original bed and water depth condition (). Individual nodes are represented as grey rectangles and identified using the subscript . Water depth is represented as light blue rectangles. b) Bed and water surface elevation is altered at nodes and at the end of time . However, water depth remains constant. The same length that the bed descends at a specifical node is what the water surface elevation descends, and , where and are the change in water surface and bed elevation, respectively. Segmented black and blue lines represent the location of the water surface and bed elevation at . c) Local correction to water surface elevation is applied at all nodes that share a link with nodes that had changes in elevation, in this case from to . The time indicates that it is an internal cycle and the simulation time does not advance while the correction is applied. Transparent light blue areas on top of water surface elevation indicates the elevation at time .

# 6 Possible future modifications

The examples included with riverBedDynamics only cover a small portion of all the possible scenarios than can be handled thanks to the Landlab components design are developed. For example, a third component can be easily added to study vegetation competition, for instance VegCA, under a non-steady sediment transport regime. Although we tried to make riverBedDynamics as general as possible, there is enormous possibilities to improve and extend the component. For example, a locally variable Manning’s roughness that varies in time as a response to bed grain properties and water depth, for example that of Limerinos (1970), could be implemented. Bank erosion and channel migration are not explicitly included in riverBedDynamics. Adding these capabilities could improve predictions and make long-term simulations more realistic. Simulation execution time could be improved by implementing a morphological acceleration factor (Morgan et al., 2020). So, in slowly changing bed processes the morphology can be calculated less frequently, thus saving time and extending the use to landscape evolution runs for timescales of millennia or longer. Calculations of bed load transport in mountain rivers, especially those with high gradient longitudinal slopes, could be more accurate by implementing the equations developed by Schneider et al. (2015) or Yager et al. (2007, 2012). Thus, effects of large roughness elements or sediment supply conditions can be explicitly included in estimates for these environments. Another possible modification that may improve simulations prediction is including a critical shear stress that evolves as a function of the sediment transport rate in a given reach similar to that of Johnson (2016)

# 7 Conclusion

Here we present the first version of riverBedDynamics, a Landlab component designed and built to simulate 2D sediment transport and river bed evolution with special focus in gravel-bedded rivers. Coupling riverBedDynamics to a modified version of OverlandFlow created a LEM that can be used to obtain accurate and detailed predictions of bed surface evolution in terms of elevation and GSD. This new LEM is physically based and solves fundamental governing equations such as the conservation of mass in the case of riverBedDynamics and mass and momentum in OverlandFlow, making it reliable when simulating unsteady processes. The new component is flexible enough for short- and long-term simulations depending on the number of processes that can be included in each case. We compared the predictions of our LEM to analytical and previously reported solutions and observed that it predicts with great accuracy changes in bed surface elevation and grain size distribution. Purely erosional and depositional cases were evaluated and both cases processes were well captured by our LEM. Using a synthetic watershed we illustrated how bed evolution and rainfall intensity distribution in time affects the flow discharge and changes in bed surface elevation across the domain.

When designing this first version we tried to make it as general as possible to represent sediment transport processes. However, there is still large room for improvement and generalization. Still, our LEM showed that combining these two components, OverlandFlow and riverBedDynamics, have the potential to simulate many of the typical scenarios found in practical management cases and scientific research. Future developments should be aligned with better representing bank erosion, channel migration, and local angle of repose effects.

# 8 Code and data availability

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