 doi:10.20944/preprints201906.0161.v1

Review

On the main components of landscape evolution models

Michael Nones [1]

[1] Department of Hydrology and Hydrodynamics, Institute of Geophysics, Polish Academy of Science, Warsaw, Poland; mnones@igf.edu.pl

* Correspondence: mnones@igf.edu.pl; Tel.: +48226915776

Abstract: Currently, the use of numerical models for reproducing the landscape evolution of a river basin is part of the day-by-day research activities of fluvial engineers and geomorphologists. However, despite landscape modelling is based on a rather long tradition, and scientists and practitioners are trying to schematize the processes involved in the evolution of a landscape since decades, there is still the need for improving both the knowledge of the physical mechanisms and their numerical coding. The present review focuses on the first aspect, discussing the main components of a landscape evolution model and their more common schematizations, presenting possible open questions to be addressed towards an improvement of the reliability of such kind of models in describing the fluvial geomorphology.

Keywords: numerical modelling; landscape evolution; surface processes; river networks

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1. Introduction

This paper reviews the state-of-art in computational models of landscape evolution, focusing on the main processes typically schematized in numerical codes that can be applied for describing terrains shaped by a combination of fluvial and hillslope processes. Indeed, nowadays numerical models represent an indispensable tool for assisting geomorphologists in reproducing the diversity, origins and dynamics of surface landscapes, combining a quantitative characterization of terrain with various theories describing the continual modification of topography by the manifold processes that sculpt it [1].

Since the 1980s, the ability of engineers and geomorphologists to measure the topography of river beds and hillslopes has grown tremendously, moving from topography maps, very imprecisely and requiring a massive work to be updated, towards digital elevation models and digital maps, generally having a higher resolution and covering the majority of the emerged landmasses [2]. In addition, the recent development of high-resolution mapping tools like laser scanners and cameras assured a very detailed and reliable description of the terrain changes in a rapidly growing part of the Earth's surface. Meanwhile, theories of landscape evolution have grown in nature and sophistication. As recently as the second half of the last century, the phrase "landscape evolution model" meant a word-picture describing the sequential evolution of a landscape over geologic time while, by the end of the 20th century, this term had taken on a new meaning: a mathematical theory describing how the actions of various geomorphic processes drive (and are driven by) the time-evolution of the basin topography.

In geophysics, primary drivers are generally described by means of a system of partial differential equations, which originate from the classical mechanical theory (e.g., describing heat, water and sediment transport, or rock mechanics). The scale dependency of such processes complicates the analysis of feedbacks and interactions between them [3]. Therefore, depending on the scale of representation, models can be computationally intensive and thus typically limited to a small spatial scale if strictly adherent to the theory, or addressing large scales with a reduced computational effort, but introducing simplified equations [4,5]. For addressing problems acting at the landscape scale that involve a greater number of coupled state variables, a variety of approaches

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is available nowadays. Modern landscape evolution models couple hillslope, channel, tectonic, and even vegetation processes by linking physically-based equations that are simplifications of the real world (e.g., gradient-flux equations, geomorphic transport laws) and/or semi-empirical (e.g., organic accumulation equations). In addition, these models are able to combine stochastic (e.g., probabilities of sediment detachment; vegetation encroachment) and deterministic (e.g., water flow velocities; bank failure) dynamics [1,6, 7].

Given that many of the most used landscape evolution models are typically run over large domains and are computationally intensive [1,6], geoscientists are also facing the challenge of reducing the computational and representational detail in models to a minimal level. As an example, Stark and Passalacqua [8] developed a highly simplified landscape evolution model as a set of low-dimensional, coupled dynamical systems to explore the coevolution of biomass and regolith under mass wasting and runoff erosion. An even more simplified approach was proposed by Nones et al [9], who tried to describe the very long-term evolution of a river basin by applying, at the watershed scale, a 0-D lumped hydro-morphological model. The popular, alternative strategy of cellular automata modelling involves abstracting the physics governing fluid flow or sediment transport to discrete rules that route parcels of water, air or sediment based on information from surrounding model grid cells [10-13]. Cellular automata strategies have made it possible to reproduce shallow flows for hydrological purposes [14], but also to simulate the development of braided streams [15,16], floodplains [17], sand dunes [18], wetland landscape pattern [19,20] and river deltas [21-23], for evaluating their response to global change and human drivers.

Aside from their physical meaning, the complexity of the governing equations of landscape evolution requires a numerical solution method to be solved in a closed form. Nowadays, the term "model" has often come to refer to both the underlying theory and the computer programs that calculate approximate solutions to the equations, involving possible misunderstandings. The growing sophistication in landscape models, accompanied by the advances in computing techniques and topographic data, has revolutionized the ability of geomorphologists to measure landforms and their rates of change, as well as to explore and numerically reproduce how these forms and dynamics arise from the fundamental physics and chemistry of geomorphic processes [1].

2. The rationale of the research

In the 1950s and 1960s, the discipline of geomorphology turned from a qualitative approach towards a more quantitative analysis of landscape evolution [24]. Starting from the 1970s, there have been a growing number of review papers covering landscape evolution models and various aspects of geomorphic modelling [see, among others, 5,25-33], offering a wide vision on the field. However, a limited number of them focuses on the theoretical and mathematical description of the involved processes, as well as the simplifications and the algorithms adopted for solving the partial differential equations governing the landscape evolution, and the formation of river networks. In fact, the focus of this paper is on landscapes that are organized around drainage basins and networks, including those in which the majority of sediment and solutes generated on hillslopes is transported away by flowing water through a drainage network. Therefore, are here not considered cases like eolian landscapes (arid regions where is the wind the major driver of mass transport), heavily karstified terrain (such as cockpit karst landscapes, in which most of the mass transport takes the form of groundwater transport of solutes), ocean floors (where the dominant processes are mass movement and density currents) and glacial terrain (in which the bulk of mass is transferred by ice). The motivation for focusing on fluvial landscapes is because drainage basins and networks cover most the Earth's land surface and because they represent one of the most human-impacted environment.

The application of landscape evolution models to river basins can provide additional insights on the various physical and chemical surface processes that interact to shape the basin and transfer mass from one place to another. Moreover, the opportunity to have a graphical representation provides a stimulus to the imagination and enhances the ability of scientists to interpret possible changes of the landscape and to quantify the consequences of various hypotheses about process dynamics. Landscape evolution models have also been used for evaluating the development of specific features like passive

 doi:10.20944/preprints201906.0161.v1

margins [34-37] or mountain chains [38-40]. Numerical models can be applied focusing on the long-term evolution of landscape [33] and river systems [41,42] or to evaluate tectonics and other surface processes [43]. Under an environmental point of view, landform evolution models can be used as tools to evaluate and manage degraded landscapes, abandoned mines [44,45], contaminated sites [46] or for projects involving landscapes affected by disturbance of soil and/or vegetation [47]. Because landscape evolution models allow to visually evaluate the temporal changes of the surface in terms of elevation, catchment size and shape, they can support the study of dynamic phenomena like gully network development and valley alluviation, which is generally not possible with fixed-terrain models based on the classic USLE approach [48]. In addition, the flexibility of these models permits to evaluate and potentially combine simulations of processes acting at a spatiotemporal different scale, spanning from short-term soil loss along single hillslopes [49,50] to catchment-scale assessments over geologic time [51-53], eventually coupling geomorphic and tectonic models [43].

Regarding the mathematical description of erosion and transport rate adopted in landscape models, Carson and Kirkby [25] discussed a variety of 1-D models of hillslope evolution under different geomorphic scenarios, while Dietrich et al. [54] provided an overview of rate laws for both hillslope and channel processes. Describing their codes, Willgoose [6] and Coulthard [27] provided a perspective on their strengths and weaknesses, showing that several solutions for reproducing the evolution of terrestrial landscapes exist. Many contributions were also focused on the general and philosophical issues relevant to geomorphic modelling. As an example, Carson and Kirkby [25] firstly and then Kirkby [26] discussed the theoretical underpinnings of the modelling approach adopted by many fluvial landscape evolution models, pointing out their role in improving the dialogue between the theory and the experimental approach. Focusing not only on landscape evolution models but also on the numerical modelling in general, Oreskes et al. [55] provided a philosophical perspective on the code structure and problems associated with verification and validation. Mimicking this approach, other works showed the limitation of adopting numerical models for describing the nature complexity [5,30,56], proposing open questions to be addressed in the future by means of new methods.

Moving from the work of Tucker and Hancock [1], this paper discusses the structure and the constitutive equations of landscape evolution models in a relatively simplified way, aiming to provide the reader with a general overview rather than with a complex mathematical description of the phenomena involved.

3. Main components of a landscape evolution model

A landscape evolution model is constituted by manifold interconnected components, mainly summarized in: i) an equation (or a system of equations) to describe the mass continuity; iii) geomorphic transport functions [1] for describing the generation and movement of sediments and solutes on the basin hillslopes; iv) geomorphic transport functions to reproduce the erosion phenomenon, the water flow and the transport of water-sediment mixtures [54]; iv) a representation of runoff generation and the routing of water across the landscape; v) numerical methods for discretizing the solution in space and time, aiming to obtain approximate solutions of the governing equations.

3.1. Continuity of mass

Geomorphic systems are rather basic systems, where the mass is conserved absolutely. However, there are many possible frameworks for addressing the continuity of the mass in a geomorphic system, depending on the kind of process reproduced and the circumstances under study. Each of these possible approaches has its own assumptions and limitations, with their pros and cons. Therefore, system modelling can be considered, to some degree, as a subjective research field, given that the included components, the adopted methodology and technology are arbitrarily assumed by the researcher depending on the case study.

Starting from the description of the mass conservation, the rate of change in mass in a given control volume V can be derived by comparing the mass rate entering the volume with the one going out (Figure 1). In other words, the process (rate of change) can be computed as a result of the nature and geometry of the idealized model (mass rate difference in-out).

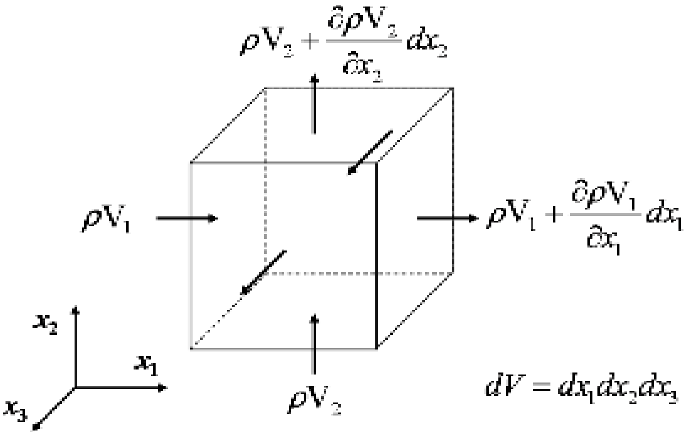

Figure 1. Schematic representation of the mass continuity in the volume *V*.

One of the most common continuity expressions in geomorphic models assumes that the control volume can be schematized by means of a thin vertical column of rock and/or soil. From this general theory, the modeller can introduce multiple simplifications related to the density or the thickness of the considered material, as well as on its porosity and grainsize.

Typically, landscape evolution models consider that all the surface is composed by rock or by a combination of rock and sand. In the first case, assuming that the surface height is a single-valued function of the horizontal position involves the impossibility to represent vertical faces and overhangs. In addition, variations in height due to compaction or expansion of the underlying soil are ignored, as well as changes in the thickness or properties of the soil layer. This latter hypothesis means that effects like the potential dependence of sediment transport rate on regolith thickness [25, 57-60], and potential feedbacks between soil water storage capacity, runoff generation, weathering and sediment transport [61,62] are ignored. On the other part, assuming that a contact between the loose, mobile regolith and the underlying rock exists provides a slightly more complete approach, but still many simplifications are present [63-68].

Despite being largely implemented in landscape evolution model, the vertical-column continuity approach can result too much simplistic. Indeed, there are several landforms that do not fit into this framework, including those with vertical or overhanging faces like cliffs, waterfalls and gully headscarps. Another limitation of the popular 2-D continuity frameworks is their inability in representing vertical variations in weathering rates, shallow flows and rock properties. For overcoming this limitation, a fully 3-D approach is therefore necessary, subdividing the column vertically and introducing equations able to represent the vertical variations in soil properties as well as the vertical fluxes of mass due to the soil strain and the advection of soil layers towards (or away from) the eroding (or aggrading) land surface [1].

3.2 Hillslope processes

The theoretical core of a landscape evolution model is represented by the geomorphic transport functions, which generally are site-specific and could have a very different nature and purpose [54].

Processes acting in the critical zone (namely, the zone bounded by the top of the forest canopy and the base of the weathering horizon [69]) weaken rock through mechanisms like fracturing, mechanical wedging, chemical alteration, biological disruption and mixing, etc. Although such weathering processes are well-studied, their mathematical representation is a rather new field of research, which is mainly focused on predicting rates of change and patterns of rock disintegration induced by specific chemical and physical processes [70,71]. Moving from the original intuition of

Gilbert [72] revised and analytically expressed by Ahnert [62], one can observe that, assuming a constant rate of regolith production from bare bedrock and a fixed characteristic decay length scale, under quasi-steady conditions (i.e., the thickness of the regolith changes very slowly with respect to the rate of surface erosion), an inverse relationship between regolith thickness and erosion rate exists. This simple prediction has been tested in several field cases, resulting in being consistent in manifold environments, ranging from semi-arid coastal mountains to high alpine terrain [67,68,73,74]. The mathematical formulation of this process can imply several assumptions, but, generally, the obtained decay curve has an exponential trend [62-64,75,76]. In his papers, Kirkby [61,77] developed an alternative to the exponential-decay models: instead of assuming a sharp contact between bedrock and regolith, he described the transition from rock to regolith as a gradational process in which the state variable is the deficit of soil, represented by the fraction of intact (unweathered) rock remaining at a particular level in the soil profile. This approach results more appropriate for describing a wide interface zone between unaltered parent material and fully weathered, mobile soil. Even if successfully tested in several studies, the exponential-decay rules cannot be considered as a conclusive solution for describing the observed regolith-thickness patterns. Indeed, further research on the mechanics and chemistry of weathering processes is needed to determine the mathematical functions that relate rates of rock disintegration to factors like subsurface temperature [78,79], state of stress [80,81] and rates of mineral alteration [70,82].

To reproduce the long-term phenomenon of soil creep on low-gradient basins, a linear slope dependent transport function can be adopted [83], accounting for the convex-upward hillslope profiles. Even if widely and successfully applied in may research field since decades, including fault scarps and fluvial, marine and lake-shore terraces [see, among many others, 84-102] and calibrated against field data derived from cosmogenic nuclide mass-balance measurements [67,68,73,74,103], the calibration constant is still the main source of uncertainty. In fact, an estimate of its magnitude can be obtained from a variety of approaches [104] and for specific processes [76,105-108], but, under a general point of view, it should be treated as an empirical parameter. Although a linear relationship, with a constant parameter, provides reliable results, physical considerations suggest that the regolith thickness can influence the soil creep equation. Many depth-dependent creep functions have been suggested in the literature [63], spanning from very simplified [90] to more sophisticated [25,60,76,105] approaches. However, despite the recent rising of specific studies, it is evident that more research is needed, especially considering landscape having steeper gradients close to the angle of repose for natural soils [68,107,109-112]. A few non-linear relationships were proposed [57,107,109,113], but, generally, such formulas result too site-specific and not completely physically-based.

Transport functions for other types of mass movement like shallow, rapid landsliding are more problematic. In fact, there are two general approaches that can be adopted for describing such phenomena: flux-based models and event-based models. The first kind of models approximates a natural series of events in terms of the resulting long-term average rate of mass transfer from point to point, using a transport function [114]. They are capable to describes the time-averaged sediment transport, therefore to a time scale relevant to landform evolution, but only at the local spatial scale: the flux in a specific point is a function of the local variables, neglecting the effects of the surroundings and the significance of long-distance transport events on steep slopes [115]. In the last decades, there were many attempts to incorporate the long-distance transport effects based on expected flow paths into landscape evolution models, but many uncertainties are still evident, mainly because of the probabilistic behaviour of the sediments. Indeed, the link between transport statistics, topography and morphologic evolution suggests to use event-based models, but, even if they are more physically-rooted being grounded on the current knowledge of landslide triggering and motion, they are computationally not really efficient and therefore not widely applied and tested.

3.3 Water flow

As well-known, geomorphic works in a drainage basin are mostly correlated to running water, therefore how the water flow is handled in landscape evolution model represents a central issue.

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Despite the possible spatial discretization methods that can be adopted, a common feature between the various models is the need to reconcile the very short time scales (minutes to seasons) associated with hydrologic processes with the much longer time scales (years to centuries) associated with sediment transport and landform change.

Typically, in a 2-D model the flow field is described by means of the De St. Venant (shallow-water) equations, which represent the vertically-integrated form of the Navier–Stokes equations for incompressible, free-surface flow [e.g., 117,118]. They contain a description of the continuity of mass and momentum in two horizontal dimensions and a friction function to describe the relationship between flow resistance and fluid velocity, accounting for four main forces: inertia, gravity, fluid pressure and boundary friction. Being these equations highly complex and not solvable analytically, simplified numerical solutions should be implied, accounting for several limitations [119].

Many overland and channelized flows accelerate only slowly in space (at least when velocity is considered at the reach scale), and this translates into the gradually varied flow approximation, where the inertial terms in the momentum equation are neglected. In addition, dropping the time derivative yields the diffusion wave approximation, which applies to flows that are mainly driven by gravity and pressure gradients. In the case of small changes of the flow depth in the streamwise direction with respect to the bed morphology, is the gravity that represents the main driver of the flow, and the pressure-gradient term can be neglected to obtain the kinematic wave equations, in which the water gravity-related acceleration is everywhere balanced by the friction. For gravity-driven (kinematic) flows, the local bed shear stress results as a function of the fluid density (water and sediment mixture), the local discharge, and the bed slope and friction. In a 2-D schematization, this approximation means that the flow lines follow the topography.

Based on that approach, many landscape evolution models use a cellular routing algorithm, imposing that the water flows from a cell to the adjacent one, following the steepest descent. As one can easily figure out, cellular routing algorithms are closely linked to the spatial discretization scheme. Indeed, in a model the continuous landscape surface is represented by discrete elements, which can be simple square cells, leading to finite-difference solutions but somehow not flexible to handle. To account for more complex domains, triangular elements in a finite-element solution [120] or triangular irregular cells having the nodes connected by a Delaunay triangulation and the surface nodes area represented by a Voronoi (or Thiessen) polygon can be implied, such as made in common models like CASCADE and CHILD [121-123]. The advantages of this cell-routing approach are the simplicity and speed, but many drawbacks are present. Firstly, it is hard to handle diverging flows, which is typical of complex river systems. Moreover, the kinematic convergence of the flow depends on the width, which can be assumed equal to the grid-cell width, leading to a grid-size dependence in flow depth and velocity [10]. Alternatively, the flow can be assumed as confined to a sub-grid-cell channel feature, having a predetermined (empirically) width [36,115]. A few models have a less strict approach, relaxing the single-flow-direction assumption by means of explicit numerical solution of the steady 2-D kinematic wave equations [124] or using multiple direction algorithms in which the flow going out from a cell is split among the downslope neighbours, weighted according to the gradient in each direction. This latter type of algorithms provides a better description of overland flow on convex hillslopes and fans [125,126]. Common codes like the CAESAR [27,127] use multiple flow-direction algorithms, accounting for all the possible directions of flow propagation and the water depth, therefore providing an efficient mean of approximating a time-varying, 2-D flow field without the expense of a traditional numerical solution of the shallow-water equations.

Commonly, landscape evolution models using cell-based or kinematic-wave water routing also assume steady flow. As an example, the SIBERIA and DELIM models compute the discharge as a power function of the basin area, assuming the local equilibrium between runoff and rainfall [10,115]. However, as Sólyom and Tucker [128] demonstrated, the local geomorphology can highly affect the hydrological behaviour. Effects of spatially variable runoff generation have also been encoded and explored in drainage network evolution models, finding out that the saturation-excess runoff generation tends to enhance hillslope convexity and hillslope-channel transitions in equilibrium landscapes [129,130]. In the future, many challenges are related to modelling the feedback effects between climate, hydrology and landscape evolution in a combined way and to accounting for

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different spatiotemporal scales, overcoming the simplifications generally applied in practice [38,128,131-133].

Kinematic-wave theory provides a good approximation for channelized flows, but some problems arise in describing the 2-D evolution of landscapes because of the convergence of such assumptions [134]. The problem of flow convergence along valley axes presents an obstacle to properly capturing the transition from distributed to channelized flow, which can be somehow handled only posing major attention on the model resolution [130,135,136]). To overcome such problems, fine-detailed models using the diffusive wave theory can be developed [137], but there is the need of powerful computers for evaluating the long-term evolution of large areas, which hinder their application to real-time forecasts.

Obviously, there are differences in terms of time-scale in simulating the runoff during a storm event and the long-term evolution of a drainage basin. Many landscape evolution models deal with this imposing a geomorphically effective runoff event to describe the basin erosion. Namely, a single, steady runoff coefficient equivalent, in terms of geomorphic effectiveness, to a natural series of runoff events should be assumed. There are many examples dealing with this approach, spanning from assuming a time-averaged sediment transport equation related to an average peak discharge [138] to more complex approaches. However, all these methods assume that the event is somehow stable, while many research pointed out the need for accounting for the role of the discharge variability in time [133,138-143]. Regardless of the detail of each method, they commonly agreed that all else being equal, erosion and transport rates increase with the increment of discharge fluctuations over time, because they depend more-than-linearly on the water discharge. While there are several applications for which the effective event assumption is reasonable, recent studies proved that the time variability in hydrologic forcing has an impact on landscape dynamics and should be incorporated in the evolution model, possibly through a stochastic description of rainfall and runoff events [139,145].

3.4 Erosion and Sediment Transport

Water flow erodes the river bed with a rate limited by the detachment of particles (supply-limited systems) or by the ability of the flow to transport particles (capacity-limited systems), with a multitude of intermediate behaviour [see, as an example, 25,115,118,144,144]). Each system needs a different schematization, and the complexity varies depending also on the erosion rate: supply-limited systems result in being the simplest in terms of numerical modelling. In fact, in such systems the sediment particles effectively disappear as soon as they are eroded, leading to the continuity of the mass [115,147]. In this case, the erosion rate is related to the bed shear stress, therefore on the local slope and discharge, giving rise to the so-called "stream power erosion law" [147,149]. A key property of these systems is the wave-like nature: there is a tendency to form erosional fronts that propagate upstream [115,150-152]. In the case of capacity-limited systems, the erosion rate depends on the unbalance between inflowing and outflowing sediments, assuming a local equilibrium in which the transport rate is everywhere equal to the local carrying capacity. This capacity-based approach is most applicable for bedload transport in gravel-bed rivers, given that coarser particles have short travel distances, so the assumption of immediate adaptation of the transport rate to changes of discharge or slope is reasonable [153]. It is less appropriate for suspended load because it essentially ignores the time required for sediment grains to settle out the water column in response to a transient hydrology. This mechanism requires the definition of a continuity mass equation for sediments in the water column, as well as detachment and settling functions, which are generally correlated with the local shear stress and grainsize [38,154-156]. There is a multitude of formulas for describing the erosion and sediment transport phenomena in a river system, but, despite this, they perform in a very similar manner if looking at the longitudinal river-profile evolution under steady conditions [42,144]. However, many differences arise in applying the models in transient conditions [151,157-159], suggesting the need for using natural experiments to test landscape models [160].

To be effective in describing the natural environment, a landscape evolution model must capture the transition from hillslopes to channels, and the degree to which landscape dissection varies as a function of factors like relief elevation, climate and lithology [114,130,161]. The distinction between channels and hillslopes can be explicitly treated, but introducing hardly describable parameters [10], or describing channels as sub-grid-scale features in which the width of the flow is prescribed empirically [36,163]. Depending on the problem under study, models can be built for representing large-scale mechanisms without requiring a very fine detail [35-37,162,164] or to reproduce the evolution of small-scale landforms, implying a grid resolution that can be smaller than the channel width [47,136,165]. For having the order of magnitude of the scales involved, one can consider a regime equation in its original form, correlating the river width with the square root of the bankfull discharge [166] or to a derived form [167,168]. Following this approach, one can see that channels are typically some orders of magnitude smaller than the whole basin, meaning that they are effectively handled as sub-grid features in landscape evolution models.

Also without having a proper background in fluvial morphology and going to deep in analyzing sediment transport equations and erosion functions, the importance of the channel geometry and scale is clearly evident: the more confined the flow, the greater the shear stress and the unit stream power, and the greater the rate of sediment detachment and transport. For speeding up the computation, some models lose their physical meaning, imposing that the erosion can be computed from the total discharge rather than from the specific one [35,138] or implying empirical regime equations [115,151]. On the one side, the use of empirical scaling laws has the advantage of calculating the cross-section averaged shear stress and stream power and applying physically-based erosion/transport functions that depend on these quantities. On the other side, relying on scaling laws for channel geometry has some drawbacks like the application of an equilibrium assumption to describe non-equilibrium dynamics [169] or the impossibility to describe rivers affected by external forcing factors like tectonics or lithological discontinuities [9]. Recently, models have been developed to represent bedrock channel evolution [170-172] and changes in channel width [158,168,169], as well as debris flows and related granular flows [173-175], but there is ample room for improving them towards a more reliable estimate of landscape evolution, accounting for physically-based laws, as well as spatially and temporally variable functions, for representing the geological and climatological variability.

4. Conclusions and Open Questions

The present review proposes a short overview on landscape evolution model and their main components, showing that, even if characterized by a quite long history [63], this research field is still very active and several improvements are forecasted for the future for answering to some open questions towards a more reliable representation of the Earth's surface.

As for the geomorphic transport functions, additional research can be focused on the evaluation of the dynamics associated with varying grainsize distributions, the role of lithology, the horizontal movement of geomorphic features due to processes such as scarp retreat and tectonic displacement, as well as the role of biota, the dynamics of stream-channel adjustment, erosion and transport by woody and debris flows and other mass movements, and the formation and evolution of the critical zone [176]. In summary, there is an evident need for a better understanding of the physical, chemical and biological controls having a role in modelling the landscape forms. Even if is the importance of the sediment dynamics is well-recognized [177,178], a major focus should be posed in understanding the grainsize production, transport and sorting in shaping the river system, given that such aspects received some attention only recently [47,179- 184]. Moreover, further research shall be devoted in better understanding and modelling the links between climate, relief, and grainsize delivery to sedimentary basins, aiming of obtaining a most reliable estimate of the processes acting at the basin scale. Fluvial transport capacity and competence are highly sensitive to grainsize composition, and, consequently, phenomena like abrasion, weathering and armouring can have a significant impact on the transport mechanisms [181,185,186], pinpointing the opportunity of considering them in landscape models at the small scale [187,188] or to justify their absence in the case of basin-wide approaches [9,42].

The geometry of river channels represents another challenge for landscape evolution modelling given that the shape and size of a channel controls (and is indirectly controlled by) the distribution of friction and energy dissipation across its wetted perimeter. There is an increasing number of numerical and experimental studies focused on evaluating how the channel geometry adjusts to base level controls, tectonic tilting, and water and sediment supply [e.g., 170-172,189,190], but these relationships are far to be fully understood. Models that couple landscape evolution with vegetation dynamics have begun to appear and are becoming a major research field [17, 168,191,192], but the scientific community has only just started to establish quantitative relationships between hydrological, biological and geomorphic processes. In addition, challenges posed by modelling such mechanisms are related also to their spatiotemporal scales, which could be significantly different [193,194].

Aside from the mathematical schematization of the processes involved and the computing challenges, one of the greatest limitations in widely applying landscape evolution models is the lack of data and methods to test them. Essentially, the reliability of landscape evolution models can be assessed through four ways, depending on the process under evaluation [1]. First, in the case of rapid landform development measurable in time-scales of months or years, such as in the case of gully formation and post-mining landscape [195], the model predictions can be directly tested against observations. However, because of uncertainties in understanding delayed effects of processes like vegetation encroachment and weathering, problems can arise in extrapolating information from such newly created landscapes to the long-term [196]. Second, in some situations real-time measurements of sediment and solute fluxes provide a useful basis for evaluating the model performance, even where the rate of landform change is slow [49,196]. Third, the development of landscapes can be evaluated by means of scaled experiments, where the involved process can be adequately measured under a controlled environment. Since decades, laboratory experiments are very helpful in addressing specific issues focusing on a few geomorphic features [see, among many others, 197-202], but, generally, they perform well only under a qualitative point of view. The recent development of high-speed computing and digital photogrammetry permitted to overcome the operative limitations present in the past towards a quantitative estimation of the landscape evolution at the laboratory scale [203], which could ultimately support numerical models. Indeed, because of many limitations correlated to laboratory tests [1] and parameters uncertainty [58], physical experiments and numerical model should be combined to adequately reproduce complex landscape changes. Fourth, models can be tested by comparison with natural experiments, which are case studies having sufficiently constraints to allow for quantitative comparisons between observations and models [49,160]. While there is a great potential in combining natural experiments and modelling runs, the necessity to develop robust statistical measures to discriminate between different landscapes and between observed and modelled landforms remains.

Although substantial progress has been made in quantitative modelling the Earth's surface, much remains to be accomplished. On the one part, there is the need for refining and testing landscape evolution models in a larger variety of cases to cover a multitude of spatial and temporal scales, by means of new and improved computing techniques. On the other part, one of the major challenges lies in developing experimental and field-based datasets for testing numerical models across a range of space and time scales and covering different geomorphic environments. Moreover, the human-induced climate change is having a major role in reshaping geomorphic systems, altering the natural relationship between the components and posing additional challenges to river modellers.

Author Contributions: M.N. analysed the available material and wrote the review.

Funding: This work was supported within statutory activities No. 3841/E-41/S/2019 of the Ministry of Science and Higher Education of Poland.

Conflicts of Interest: The authors declare no conflict of interest.

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