Response to referees for "The Landlab v1.0 OverlandFlow component: a Python tool for computing shallow-water flow across watersheds", by Adams et al.

Dear Dr. Neal,

Please find below our comments in reply to each of the reviewers and commenters: Dr. Astrid Kerkweg, Dr. Dapeng Yu and Dr. Katerina Michaelides. Per the instructions provided, we have pasted below copies of their letters, and our responses. Dr. Kerkweg's comment was brief, so we have simply replied to her comment in the form of a letter. For the letters from Dr. Yu and Dr. Michaelides, we responded to each comment within their letter, with our comments in italics. Also attached is a PDF of tracked changes from the original LaTex draft to the revised copy.

We hope these comments address the concerns of the reviewers to their satisfaction, and to yours. Thank you for taking the time to handle and review this manuscript. We look forward to hearing from you.

Many thanks again,

Jordan Adams (on behalf of all the authors)

Comment from Astrid Kerkweg

Dear authors,

In my role as Executive editor of GMD, I would like to bring to your attention our Editorial version 1.1: http://www.geosci-model-dev.net/8/3487/2015/gmd-8-3487-2015.html This highlights some requirements of papers published in GMD, which is also available on the GMD website in the 'Manuscript Types' section: http://www.geoscientific-model-development.net/submission/manuscript_types.html

In particular, please note that for your paper, the following requirement has not been met in the Discussions paper: • "The main paper must give the model name and version number (or other unique identifier) in the title." Please add a version number for the Landlab OverlandFlow component in the title upon your revised submission to GMD.

Yours, Astrid Kerkweg

Response to Astrid Kerkweg

Dear Dr. Kerkweg,

Thank you for your guidance regarding the title of the manuscript. We have updated the title to reflect that the OverlandFlow component is part of Landlab v1.0. We believe this addresses the requirements you addressed in your comment. Many thanks again,

Jordan (on behalf of all authors)

Response to Dapeng Yu

Dear Dr. Yu,

Thank you for taking the time to review our manuscript. We appreciate the detail you have put into your comments and believe your suggestions have strengthened the manuscript. Below we have replied to each comment in italics, addressing the concerns regarding the original manuscript.

Many thanks again,

Jordan (on behalf of all authors)

I enjoyed reading the article. It reproduced a 2D inertial based flow routing algorithm within an earth surface dynamics modelling package. I made quite a few comments/inquires in the document attached but the major comments are summarized below. I didn't comment on the sediment transport bits very much as I don't have the expertise in that area.

We thank Dr. Yu for his comments.

General comments

1. The writing needs to be improved. It is unclear at the first read in many places. A lot of polish is needed to make the texts more concise and remove the unnecessary bits. This needs quite a bit of work in my opinion.

We appreciate the time you have taken reviewing the document. We carefully reviewed all of the comments in the PDF supplement, addressed them and have commented in more depth below.

2. Structure can be improved to follow the typical/classic way of journal paper writing. In particular, background sections within the two test cases should be incorporated into the introduction so readers can get a sense of the overall context of the work you undertook.

We have restructured the paper per this suggestion, moving the two application "background" sections into the introduction. The introduction was then edited to improve the flow.

3. The design of the tests is rather unstructured and in many ways rather random, often un- or not justified properly. A few sentences here and there are needed to justify the choice of rainfall intensity and design of tests.For example, why 5 mm/h storm - is this based on real events? Why two catchments with different shapes and how the relief is designed?

The assumptions regarding infiltration and precipitation have been added to the text. These assumptions were used to keep the tests simple and replicable, as the codes are made publicly available so readers may test the component on their own.

The test design was also explained more clearly in the text. Regarding the storm durations and intensities, these events were selected based on real data. For example, a 1-yr, 60-min precipitation event in semi-arid climate in central Colorado has a total depth of approximately 12 mm. To simplify, a 10 mm storm depth was used. This storm depth was held constant so that results could be easily compared, but was then applied across different durations to test for differences in hydrograph shape and incision depth.

Finally, the basin shape was changed to see if hydrograph shape changes with basin organization. This is mentioned in the introduction and is also clearly explained in *section 7 and subsections, where the model set-up for the synthetic landscapes application is outlined.*

4. Sensitivity to resolution and roughness needs to be investigated. Whether changing mesh resolution will change the hydrograph shape? What are the impacts of roughness? I suggest simulations to be designed and a graph or two to be included for test case 1 where the authors demonstrate the model's response to these two parameters.

This was an excellent suggestion. We more clearly stated how the existing analytical solution (now Fig. 7) can be used to analyze model sensitivity to roughness. We also clarified the range of Manning's n values used in that test, to illustrate how it captures a range of natural roughness values from urban landscapes to more heavily forested watersheds.

A new figure (Fig. 6) and section (5.1) were added to outline how sensitive the model is to changes in grid resolution, following the solution in Bates et al., 2010.

5. It is rather disappointing that test 1 is not chosen in a site where real rainfall records and flow gauging records are available. Surely there are plenty of such datasets. As such the model is not validated in a robust way although patterns of hydrographs at the outlet look reasonable. A comment on this somewhere would be useful. Also perhaps highlight this for future studies?

The model was not calibrated using real rainfall records or flow data. The current model is not meant to be a predictive hydrologic model, and does not include the many other processes found in existing hydrologic models. This submission was designed to merely illustrate the capabilities of the model.

We have also added a sentence about the rationale for using the Spring Creek watershed for our model runs, in section 6.

<u>Specific comments</u>

[1.6] This sentence should be before the last one as it tells the readers what is Landlab

The abstract has been reworded and Landlab is now properly introduced before any other reference is made to it.

[2.2] Many more recent papers on urban flood modelling from various are available. I suggest including a few to recognize the recent developments in the field.

Good suggestion. We have added new references about overland flow modeling in urban landscapes.

[2.9] not all the references therein are relevant. This can be removed.

Removed.

[2.13] Make it specific - computational mainly and solving the equations

This sentence has been clarified to state complexity comes from solving the equations.

[2.31] change "may never" to "can rarely"

Changed.

[4.19] I found this is hard to follow but the figure is very useful. State clearly an open boundary is where inflow is taken into the system (I assume). Active nodes are those receiving water. Rainfall can be used as I read on... so on and so forth.

We have updated the text to state clearly how the model behaves on different grid elements, per their boundary condition (e.g. rainfall is applied on core nodes, fluxes are calculated on active links).

[5.3] not for the 1D case which is fast. It is only when it becomes 2D what states here applies.
Clarified to specifically state the 2D case.

[6.28] This was not mentioned earlier on - mentioned afterwards so need to bring it in earlier or here..
We have added a reference to the steep_slopes flag much earlier in this section.

[7.7] and its
Changed.

[7.28] LisFlood-FP reads in ASCII files as far as I know. So I think this is an overstatement - I don't think Landlab simplifies this as both are doing the same - i.e. reading in ASCII files, which need to be prepared for the simulation site.
Reworded, and removed text that implied Landlab simplified this process.

[8.7] Can there be multiple outlets? In urban applications, this may well be the case.
We first specified that the set_watershed_boundary_condition method can only operate on a watershed with a single outlet. Added specific reference to the type of situation mentioned here: multiple outlets. This new text states that if a user requires multiple outlets, they can set those boundary statuses manually.

[9.1] Will there only be incision? Will there be deposition? No expert in this field but assume this happens during land evolution?
The model described here only looks at incision, no deposition. This is not unreasonable compared to existing landscape evolution models. The OverlandFlow component can be coupled with sediment transport (erosion and deposition) in other applications, as described in the Future Applications section 8.
This was also more clearly stated in the text, section 3.2.

[9.3] Also need to mention the sensitivity to resolution from previous studies. I assume this study agrees.
We have added a new section (5.1) and figure (Fig. 6) which address the sensitivity of the model to grid resolution.

[9.3] How does the time steps compare with the published studies?
We have added text to compare minimum time steps in the analytical solution runs to the values provided in published studies of Bates et al., (2010) and de Almeida et al., (2012).

[9.16] 0.1 is high for a natural landscape... according to Chow.
While 0.1 is high, it is within the range given by Chow. 0.1 can be a representative roughness for landscapes with “very weedy reaches, deep pools or floodways with a heavy stand of timber” or channels with “dense brush”. These types of landscapes could be of interest to geomorphologists, which is why the high value was included.

Additionally, using a range of 0.01 to 0.1 demonstrates how the model behaves across a range of nearly all Manning's n values, from quite low (0.01) to quite high (0.1). The analytical solutions show the model is capable of handling all types of terrain roughness values.

The text has been updated to reflect that these two tested n values capture a range of landscape types.

[9.27] This should be moved to the introduction.

This has been moved to the introduction, and the text there has been modified to accommodate the the new sections.

[10.12] Is this used in the model?

This is calculated manually in the Landlab driver file. Data can be plotted to explore the different grain sizes that can be transported by the OverlandFlow flood wave. (Fig. 8d)

[10.14] should be water surface slope

Changed

[10.16] This can be kept here

This transition paragraph was now put at the end of section 6, as the "Background" section in the previous draft was integrated into the Introduction (See General Comment #2).

[10.29] This is not exactly what D4 does. There are depressions in the landscape which won't be removed by this I think? Can the authors explain>

This has been clarified to state that the Landlab SinkFiller component actually fills the depressions, allowing for D4 flow routing.

[10.34] unclear to me: is this uniform rainfall across the catchment? If so, why not use a more realistic or even real event with the typical shape of a rainfall episode?

All references to rainfall events have now included the assumptions about spatial distribution. Uniform rainfall was applied for simplicity. It is possible to instantiate temporally and spatially variable rainfall, but the point of this paper is to focus on demonstrating the capabilities of this software.

[11.1] Why only at the peak? Does the peak depth reach for all points at the same time - unlikely? If not, sheer stress recorded this way may not represent the maximum transport capacity.

This is an excellent point. We have updated Fig. 8 and the corresponding caption to reflect the changes to the figure. The new figure shows the maximum shear stress which occurs at each point in the domain. This can account for differences in the time to peak.

[11.11] Do we need such details here as these are known facts?

Good suggestion. Extra details were removed to keep the paragraph concise.

[11.4] Did the authors undertake sensitivity analysis to roughness and mesh resolution? This is typically required for this sort of modelling

The analytical solution section has been updated to discuss the sensitivity of the model to surface roughness (section 5.2 and Fig. 7).

A new section has been added within the analytical solution section to discuss the sensitivity of the model to grid resolution (section 5.1. and Fig. 6).

[11.7] Timings of the upstream and midstream point depth profiles are very similar. Why there is no delay for the midstream point?

While they are somewhat similar, the midstream point hydrograph does reach the peak value several minutes before the upstream-most point. In plotting the entire hydrograph, this delay is less apparent. Text was added to the figure caption to make this delay clearer.

[11.22] It would be interesting to see how this can be validated. A real event with gauging data at the outlet would be highly recommended.

As we stated in response to an earlier comment, this paper was designed to demonstrate different use-cases of the OverlandFlow component. The model is not meant to be predictive in its current form, as it still lacks processes and variables (e.g. infiltration, vegetation dynamics) that are generally considered in predictive hydrology models. Additionally, parameter tuning, model calibration to field data could constitute an entire manuscript, and were too extensive to be explored in a model description paper.

[11.28] Similar to the above section, this can be incorporated into the introduction and the last paragraph can be moved to discussion.

Background information was moved to the introduction section.

[12.28] Are the synthetic rainfall based on any particular event?

As stated before, we used simplistic cases for reproducibility and to keep the results easy to understand. As part of the model description paper, we are demonstrating use cases. The rainfall depths are not out of the ordinary for semi-arid climates like those in central Colorado, draw from NOAA data (cited now in the paper).

[13.13] So assuming 50 storms per year?

Additional text has been added to state the assumption for the base storm is 50 storms per modeled year, and 25 storms per modeled year in the higher intensity and longer duration storms.

[13.21] depth at all point

Changed.

[14.22] Isn't this expected? Don't think this is a finding.

Added a few extra words to clarify that these results were as expected.

[15.2] Not clear to me. What does this refer to? This was not mentioned in the introduction and came rather abruptly.

The Future Applications section (8) was updated to include more examples, and have softened the transition from previous sections.

[Figure 5] should be 0.4, as stated in the text?

We have double checked all labels and in text references to (now) Figure 7.

Response to Katerina Michaelides

Dear Dr. Michaelides,

Thank you for taking the time to review our manuscript. We appreciate the detail you have put into your comments and believe your suggestions have strengthened the manuscript. Below we have replied to each comment in italics, addressing the concerns regarding the original manuscript.

Many thanks again,

Jordan (on behalf of all authors)

This paper presents a new component of the Landlab model that simulates runoff generation and surface-water flows in watersheds. The novelty of this component in the context of landscape evolution models is that: (i) it represents non-steady state runoff (in contrast to other models that typically assume steady state, i.e. Q = PA) and (ii) it implements a two-dimensional hydrodynamic algorithm, the formulation of which allows for computational efficiency and stability on steep and shallow terrains. After presenting details of the algorithms and methods, the paper outlines some example simulations of the performance of the overland flow component on synthetic and real watersheds and compares against the steady-state runoff assumptions of other landscape evolution models (LEMs). Finally, the paper presents fluvial erosion simulations by coupling the flow and incision components in Landlab. I'm excited to see this new component developed and implemented in Landlab and I can see many potential applications and future developments based on it. Technically, I think it is sound and the algorithm developments are quite clearly explained. Overall, this paper will make a nice contribution to GMD and I look forward to seeing it published soon. However, in my opinion the paper requires some restructuring and editing to make it clearer, more focused and to improve the flow.

We thank Dr. Michaelides for her comments.

There are few aspects of the paper that need to be more clearly explained up front. For me these are:

General comments:

1) What are the intended timescales of application of OverlandFlow (event, year, decade, 10ˆ3y, 10ˆ4y, 10ˆ5y etc.)? If is intended to be flexible, then some discussion is needed as to how the various modes can be implemented (especially the long timescales which are not addressed in the paper). Given the myriad of watershed hydrological models out there that can do what OverlandFlow does and much more for event to decadal scales, I feel that the novelty of this component within Landlab would be better pitched as an improved flow component within an LEM.

We have tested from event to 10^4 year scales on a desktop machine. We have added specific language to both the abstract and future applications sections to reflect these timescales. In this updated text, we also added some discussion about the flexibility of the different timescale opportunities, and how high-performance computing can extend this model even further.

2) As a hillslope person, I get easily confused with phrases "throughout the watershed" as I tend to think that includes the hillslopes as well as the channel. It would be very helpful if the paper

explained more clearly what processes occur in which parts of a basin. I assume that OverlandFlow could be coupled to a surface wash geomorphic transport law (GTL) on the hillslopes? This could be discussed in section 8.

This is an excellent point. We have now clarified early on that the OverlandFlow component can route a hydrograph at all points, on hillslopes and channels. We have also changed some references throughout the text and figure captions to specify channels, particularly when hydrographs are plotted.

The future applications section also now mentions sheet-wash as a potential coupling opportunity.

3) There is no mention of infiltration until section 8 at the end of the paper. I think it would be very helpful to the reader if the assumptions are mentioned up front and if there was a clear explanation behind the rationale of effective rainfall and how this is calculated for the examples. I think there is an existing Green and Ampt infiltration component for Landlab, so I assume this can be easily coupled to OverlandFlow? Again, this would be worth discussing.

We have added several mentions to infiltration in the text now, particularly focusing on how the model (by default) assumes no infiltration explicitly. As a model description paper, we kept the assumptions simple to keep the results clear. The future work section notes coupling with infiltration as an opportunity for evaluation.

4) Hydrological theory needs beefing up in the background section as many of the model results discussed are common knowledge in hydrology. Please provide theoretical background on runoff generation, steady vs nonsteady runoff, spatial and temporal variations in discharge and the role of basin characteristics, and the impact of this runoff on erosion and incision.

All very good points. To address this, we have added a paragraph about the traditional hydrology methods, with focus on the steady-state (Q = PA) assumption.

Additionally, we added discussion about how discharge scales with temporal rainfall patterns, per the study of Huang and Niemann (2014).

Finally, there has been discussion added about the steady-state assumption's failure to capture differences in basin organization and shape, even though theoretical background in hydrology states that basin characteristics drive hydrograph shape. For example, watersheds with identical drainage areas but different basin shapes may have dramatically different outlet hydrographs not captured by steady-state assumption.

<u>Specific comments:</u>

1) Manuscript structure: My personal preference would be for the two 'Background' sections (6.1 and 7.1 on p. 9 and 11) to be incorporated into the Introduction of the paper. Much of the information in those sections is key to appreciating the new component developments (i.e. steady state vs non-steady state runoff) and the impacts on fluvial incision. The novelty of the new component (relative to typical approaches in LEMs) needs to be stated much more clearly upfront.

These sections have been moved to the introduction.

2) Abstract: The first couple of sentence do not link well to the rest of the abstract and they lack flow to the rest of the section. I'm not convinced that a couple of token general sentences about hydrological or rainfall-runoff models add anything or help direct the reader. I think what would work better would be to discuss the hydrological capabilities of LEMs and go from there. There is a plethora of very sophisticated hydrological models for event to decadal timescales, which is probably not relevant in the context of Landlab – so I'm not convinced that those are the ideal starting point for the paper. Finally, I think that the abstract should more clearly state what the

novelty of the new component is, what the assumptions in the paper are (i.e. no infiltration), and what the timescales of the application in this paper are (i.e. individual storm to 10 years of simulation). On [5] what do you mean by "longer term landscape evolution"?

We have reworded the first few sentences to explicitly outline how this model is different from traditional landscape evolution models. We have now clearly stated all assumptions, and reworded the abstract to include the timescales explored. Additionally, we clarified what is meant by traditional rainfall-runoff application of OverlandFlow (event scale) and what we mean by landscape evolution applications.

3) Introduction (p.2): The opening paragraph [2-6] is in my opinion, a slightly odd (atypical) selection of applications for overland flow models. Maybe it's just me, but I wouldn't put urban flooding and post-wildfire runoff as the top two examples of overland flow models! Again, I'm not so sure that this section is even needed. I would focus the discussion on the hydrology within LEMs which are still relatively unsophisticated in terms of hydrological processes compared to hydrological models. Because even in your improved representation, there is a lack of hydrological processes (subsurface or infiltration components), and is predominantly therefore, a flow routing algorithm (using uniform effective rainfall as a proxy for runoff generation). In other words, if you were developing a watershed hydrological model for use over short timescales (event to decades) then this would not really be considered that novel.

We have reworded this section and added several more recent citations. We want to appeal to both hydrology and geomorphology communities, so we left all of the hydrology commentary in. This is because all hydrologic processes could eventually be possible within the Landlab framework, even if they are not fully complete now.

We have also added discussion about traditional landscape evolution/steady-state assumptions, and explained how this new model and method differs from existing models.

4) p2 [12-13] merge these two sentences as they repeat the same thing.

Completed.

5) p2 [18] What is a "hydrological timestep" and a "geomorphic timestep"? Do you mean timescale?

Changed to address timescales particularly, not timesteps.

6) P2 [22] I would say most (not "many") hydrological models route storm hydrographs through basins and represent non-steady discharge. This is a pretty standard feature in watershed hydrological models.

Changed to "most".

7) P2 [30 34] and P3 [1-9] It would be helpful if the introduction included some outline of hydrological theory regarding runoff generation, steady vs nonsteady runoff, spatial and temporal variations in discharge and the role of basin characteristics, and the impact of this runoff on erosion and incision. I just feel like we're missing a step or two in fundamental theory which would provide a useful backdrop to the reasonableness or not of the various assumptions in LEMs.

This has been added, our response to an earlier comment (General Comment #4) addresses this specifically.

8) P3 [17] What is "short-term landscape evolution"? Please define "short-term" in this context.

Specified that short-term meant decadal scale runs.

9) P3 [23] "scientific problems" is too vague.

Clarified to address that Landlab can be used to address a range of hypotheses in Earth-surface dynamics.

10) P5 [21-22] "too-large timesteps" and "too-small timesteps" is awkward expression. Please reword and also define "too small" and "too large" in this context.

Moved discussion about the Courant number requirement to earlier in the paragraph, to put the timestep into context. Also changed wording to clarify the "too-large" or "too-small" timesteps.

11) Section 3.1: Please explain how rainfall is treated. I am assuming there is no infiltration component (as there is no mention of infiltration) – so how do you derive this effective rainfall rate over the basin?

A paragraph was included at the end of this section about the default behavior of the model, regarding precipitation and infiltration assumptions that addresses this.

12) P6 [21] Does "flat" mean zero slope or less than some threshold?

Changed to state explicitly that we meant low-to-zero slope environments.

13) P6 [23] "Similar criterion were implemented" – reword as either 'a similar criterion was implemented' or 'similar criteria were implemented'.

Reworded.

14) P7 [1] What is the meaning of "water discharges driven by overland flow"?

Reworded this to state that water discharges are calculated by the OverlandFlow component and used in model coupling.

15) P9, section 6.1 first 6 lines of Background feel too cursory.

This was moved into the introduction, per the earlier comment. It was also put into more context by adding more discussion and citations.

16) P10 [5-10] "Changing discharge values" unclear

Reworded this part to clarify.

17) P 10 [18] Are hydrologists the target audience here? Not geomorphologists? If so, there needs to be some discussion of the assumptions (no infiltration, no subsurface flows etc.) that hydrologists would care about.

We have addressed the assumptions in the application descriptions.

18) P10 [23] Please provide a sentence or two as to why Spring Creek was chosen as a test case.

The Spring Creek watershed was selected because there is an abundance of field data for the site, collected by the U.S. Geological Survey. This DEM has already been used in previous Landlab work (the Hobley et al., 2017 cited within this manuscript). The DEM was pre-processed for use in Landlab, and we have added text to reflect this in section 6.1.

19) P10 [32-33] Please explain why 5 mm/h for 2 hours was chosen as the effective rainfall. Is this based on real data or chosen as a typical value for that place? Is this supposed to represent

a large storm? 10 mm of uniform surface overland flow (effective rainfall) over a whole basin is pretty high.

We used an approximate depth from a NOAA dataset for central Colorado that is now cited in the text. This estimated a storm depth of 10 mm in 1 hour, with a 1 yr storm recurrence. We systematically increased and decreased duration to keep the depth the same for all storm runs. Text was added to reflect this.

20) P11 [1-2] Please explain the rationale for doing this. The peak Q at the outlet is unlikely to correspond to the peak shear stress on the hillslopes or other parts of the channel.

This was an excellent point. We have now updated Fig. 8 and text within section 6 and subsections to show the maximum shear stress value calculated each point.

21) P11 [5-15] These are not really results – it's as you would expect (basically, the model is behaving)

We have made it clear in the text that these are not results, but that the model is performing as it should.

22) P11 [22] What is the meaning of "the flow of hydrographs"?

This was an error. It has now been fixed.

23) P13 [1] "Discharge was recorded at all points throughout the watershed". Does this mean on hillslopes and in channels? Please be specific.

In these runs, there are no "true hillslopes" in this model, as the landscape was evolved using a channel incision method. This has been clarified at all mentions in the text.

24) P13 [13-15] What is the rationale for looking at 10 year simulations?

Decadal scale runs were used as they are easy to reproduce on a personal machine, using the GitHub repository associated with this paper. These results can be used to make inferences about long-term landscape evolution runs.

25) P13 [22] "all points in the hydrograph are much less than the predicted steady-state". Unclear sentence. Do you mean the non-steady discharge is always lower than the steady state discharge or that the total volume of water exiting the basin is lower?

We have updated the text to clarify this thought. Now it states that the actual discharge values represented in the hydrograph are less than predicted steady-state. The total volume of water is unchanged between steady-state and non-steady state, as all mass is conserved in the model.

26) P13 [25-30] As expected.

Changed in text.

27) P14 [3-5] What is the meaning of comparing erosion results from one single storm to geomorphic steady state?

We are comparing predicted steady-state erosion rate to the erosion drive by several events (10 years). We have now clarified this in the text.

28) P14 [13-16] This is missing some context. It is the first mention of 10 years and number of storms (intensity, duration etc.).

We have outlined this in an earlier section, 7.1.

29) P15 Section 8. First mention of infiltration here. Needs to come further up. Beyond the examples of applications of this component, here I would really like to see more discussion of how the representation of hydrological processes may evolve within Landlab in the future and how the authors envision this rainfall-runoff component will be used to simulate long-term landscape evolution driven by surface wash (on hillslopes) and fluvial incision. It would be good to see some reflection on the representation of spatial variability too (e.g. in surface properties). I think you're missing a great opportunity to sell this model and its future potential by pitching to the landscape evolution / geomorphic community.

We have added considerable discussion to the future applications section. This includes addressing the longer-term landscape evolution question and possible applications distinguishing the difference between hillslope and channel processes.

30) Fig 6: Only channel hydrology

Changed text to state that the hydrographs are taken from within the channel.

31) Fig 7: Please redefine within caption h, S, n and all other symbols used in figure.

Updated figure caption per this suggestion.

I hope this helps. I look forward to seeing it published soon, and I will attempt to use it myself at some point! Best wishes, Katerina Michaelides

The Landlab v1.0 OverlandFlow component: a Python ~~library~~ tool for computing shallow-water flow across watersheds

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Abstract. Hydrologic models and modeling components are used in a wide range of applications. ~~Rainfall-runoff models are used to investigate the evolution of hydrologic variables, such as soil moisture and surface water discharge, throughout one or more rainfall events. Longer-term landscape evolution models also~~ Geomorphologists include aspects of ~~hydrology~~hydrologic models, albeit in a highly simplified manner, ~~in order~~ when using long-term landscape evolution models to approximate how flowing water shapes landscapes over thousands to millions of years. Most landscape evolution models make assumptions that reduce overland flow into a function of drainage area and precipitation rate, removing physical parameters like water surface slope and surface roughness from flow calculations in favor of computational speed. The Landlab modeling framework can be used to incorporate more physically-based overland flow methods into traditional erosion models, an application not widely used by the geomorphology or hydrology communities. ~~Here we illustrate how the OverlandFlow hydrologic component contained within Landlab can be applied as either a short-term rainfall-runoff model or a longer-term landscape evolution model.~~ Landlab is a Python-language library that includes tools and process components that can be used to create models of Earth-surface dynamics over a range of temporal and spatial scales. The Landlab OverlandFlow component is based on a simplified inertial approximation of the shallow water equations, following the solution of de Almeida et al. (2012). This explicit two-dimensional hydrodynamic algorithm propagates a flood wave across a ~~terrain~~model domain, and water discharge and flow depth are calculated at all locations within a structured (raster) grid. Here we illustrate how the OverlandFlow hydrologic component contained within Landlab can be applied as either a simplified event-based rainfall-runoff model or a landscape evolution model operating on decadal timescales. Examples of flow routing on both real and synthetic landscapes are shown. Hydrographs from a single storm at multiple locations in the Spring Creek watershed, Colorado, USA, are illustrated, along with maps of ~~water depth and~~ shear stress applied on the surface by ~~the~~ flowing water. ~~Flow routing on~~ Results from two different synthetic watersheds ~~illustrates~~ illustrate that the model correctly captures how network organization impacts hydrograph shape. The OverlandFlow component is also coupled with the Landlab DetachmentLtdErosion component to illustrate how the nonsteady flow routing regime impacts incision across a watershed. The hydrograph and incision results are compared

to simulations driven by steady-state runoff~~, or discharge equal to the product of drainage area and rainfall rate, which is the norm in landscape evolution modeling~~. Results from the coupled hydrologic and incision model indicate that runoff dynamics can impact landscape relief and channel concavity~~. Example code is provided that demonstrates how to use~~ , suggesting that on landscape evolution timescales, the OverlandFlow model may drive significant differences in simulated topography compared to traditional methods. The exploratory applications described within demonstrate how the OverlandFlow component ~~and couple it with other components to create a model~~can be used to understand coupled patterns of flooding and erosion. Provided example codes run on a desktop machine will take on the order of hours to run simulations of $\leq 10^4$ years, assuming watersheds with similar drainage areas and grid resolutions are used.

1 Introduction

Numerical models of overland flow have a variety of applications. Examples include mapping urban flooding events ~~(e.g. Dutta et al., 2000;~~ ~~modeling hydrogeomorphologic processes in post-wildfire landscapes (e.g. Beeson et al., 2001; Rengers et al., 2016) and~~ (e.g. Dutta et al., understanding the interactions between surface and subsurface water by way of soil infiltration ~~(e.g Esteves et al., 2000; Kollet and Maxwel~~ ~~Another possible application is the study of erosion and sedimentation driven by overland flow, and how these processes can shape long-term landscape evolution~~(e.g Esteves et al., 2000; Panday and Huyakorn, 2004; Kollet and Maxwell, 2006; Maxwell and Kolle exploring hydrogeomorphologic processes in natural landscapes (e.g. De Roo et al., 1996; Beeson et al., 2001; Francipane et al., 2012; Kir Yet to be deeply explored is how hydrologic processes, specifically runoff generation, impact landscape evolution over centennial scales and longer. Pioneering work by Tucker and Bras (1998) and Sólyom and Tucker (2004) has explored this problem, but there are still unanswered questions, including how hydrograph shape impacts erosion rates and topographic patterns.

Models of landscape evolution all have the same fundamental structure: all use numerical methods to model flow or transport of water and sediment across a representative mesh that is tessellated into discrete elements~~(e.g. Coulthard, 2001; Willgoose, 2005; Tucker a~~ ~~To some degree, all landscape evolution software packages model interactions between hydrology and geomorphology.~~ , but the complexity of the ~~hydrologic component varies (e.g. Willgoose et al., 1991; Tucker and Slingerland, 1994; Willgoose, 1994; Braun and Sa~~ mechanism varies (e.g. Willgoose et al., 1991; Tucker and Slingerland, 1994; Willgoose, 1994; Braun and Sambridge, 1997; Tucker et al., The representation of ~~hydrological processes~~ surface water flow in landscape evolution models is often simplified, as ~~there are complexities when~~ solving the shallow water equations can be computationally intensive. Most models assume unidirectional steady-state water discharge, where surface water flux is modeled at each location as a ~~function~~ product of drainage area and ~~precipitation rate, and flow is only present in the system~~ rainfall rate, or:

$$Q_{ss} = PA \quad (1)$$

where Q_{ss} is the steady-state water discharge $[L^3T^{-1}]$, P is an effective precipitation or runoff rate $[LT^{-1}]$ and A is drainage area $[L^2]$. Discharge increases moving downstream with drainage area, but only lasts for the duration of a precipitation event ~~. Flow routing algorithms can be simplified as well, limiting flow to travel along the steepest descent out of a given location (Tarboton, 1997; Tucker et al., 2001; Tucker and Hancock, 2010). These simplifications are often~~ and stops when precipitation ends. If the precipitation rate is constant, the discharge rate at a given point in the domain will be constant for the duration of the model run, creating a rectangular hydrograph (Fig. 1). In more physically-based hydrology models, the steady-state assumption is replaced with nonsteady runoff processes that simulate a flood wave moving across a watershed. Figure 1 compares the steady-state discharge assumption to the nonsteady method at one location in the watershed. The effective rainfall rate P is the same rate and has the same duration for both the steady (Q_{ss}) and nonsteady (Q_h) discharge simulations. The nonsteady hydrograph (Q_h) lasts longer through time than steady-state discharge (Q_{ss}), as it is controlled by the physical nature of the system, such as local water depth (h), surface roughness (n) and water surface slope (S).

The simplifying assumption of steady-state discharge is made for two reasons: there can be significant differences between hydrologic ~~time steps~~ timescales for individual flood and storm events (~~seconds~~ minutes to days) and geomorphic ~~time steps~~ timescales of rock uplift and landscape evolution (~~years to millennia~~thousands to millions of years) that may be complex to resolve~~; additionally~~. Additionally, computational power ~~may be~~ is often a limiting factor, and these simplifying assumptions ~~may~~ speed up the model processing time.

Whereas many geomorphic landscape evolution models generalize ~~hydrology~~ surface water flow using steady-state assumptions, most hydrologic and flood inundation models ~~that~~ route a storm hydrograph (changing discharge through time), capturing the spatial and temporal variability of water discharge across a modeled landscape ~~(e.g. Bates and De Roo, 2000; Ogden et al., 2002; Down~~ (e.g. Bates and De Roo, 2000; Ogden et al., 2002; Downer and Ogden, 2004; Ivanov et al., 2004; Hunter et al., 2007; Moradkhani and Sor These models, often referred to as 'rainfall-runoff' models, are applied over real landscapes to simulate overland flow events. Surface water runoff is one of many physical processes and parameters explored in these models. Lumped rainfall-runoff models represent watersheds as characteristic subareas or subbasins, and do not account for spatial variability in physical subbasin parameters. These models assume that average variables and parameters adequately capture the processes being modeled (e.g. Donigan et al., 1984; Scharffenberg and Fleming, 2006; Moradkhani and Sorooshian, 2009; Beven, 2011; Devi et al., 2015)

Alternatively, domains within distributed rainfall-runoff models are broken into smaller, discrete elements or grid cells. Distributed models allow for increased spatial variability in model parameters or state variables (e.g. Beven and Kirkby, 1979; Woolhiser et Some of these hydrologic models have been paired with erosional models at the watershed scale ~~(e.g. Aksoy and Kavvas, 2005; Francipane~~ However, there are a limited number of studies that integrate a physically-based~~hydrologic model~~, distributed runoff method into a landscape evolution modeling framework~~, due to the challenges previously discussed.~~; the steady-state discharge assumption (Eq. 1) is often used instead.

The assumption of steady-state ~~runoff~~ discharge in landscape evolution models is ~~often not~~ not always reasonable. For example, steady-state hydrologic conditions ~~may never~~ can rarely be achieved in larger catchments with long flow paths, or in landscapes dominated by short-duration precipitation events. Under these conditions, predicted steady-state discharge may not be reached in a watershed. Additionally, the traditional steady-state model (Eq. 1) does not capture differences in basin organization or orientation, while discharge is known to be sensitive to these characteristics (Snyder, 1938). For example, watersheds with identical drainage areas but different shapes or orientations may have dramatically different hydrograph shapes that are not captured by the traditional steady-state assumption.

Adding hydrologic variability in landscape evolution models has also been shown to impact watershed morphology. Previous work coupling spatially variable rainfall models with steady-state discharge in landscape evolution models has shown controls illustrated impacts on landform morphology, including relief and drainage network organization (e.g. Anders et al., 2008; Colberg and Anders, 2014; Huang and Niemann, 2014; Han et al., 2015). Similarly, introducing storm and discharge variability into landscape evolution models has implications for incision rates, channel profile form and steepness in modeled landscapes (e.g. Tucker and Bras, 2000; Lague et al., 2005; Molnar et al., 2006; DiBiase and Whipple, 2011). In contrast to these studies, Coulthard et al. (2013) integrated a semi-implicit hydrodynamic model into the CAESAR landscape evolution model and noted reduced sediment yields on decadal time scales of landscape evolution when using nonsteady hydrology. In another approach, Sólyom and Tucker (2004) estimated nonsteady peak discharge as a function of the storm duration, rainfall rate and the longest flow length in a network. Incision rates were estimated using those peak discharge values. Their findings demonstrated that landscapes evolved with nonsteady hydrology were characterized by decreased valley densities, reduced channel concavities and increased relief when compared to landscapes evolved using steady-state hydrology.

To represent and investigate the role of nonsteady flow routing on landform evolution, a hydrodynamic model has been incorporated into the new Landlab modeling toolkit. In this paper, we describe the fundamentals of the Landlab modeling framework, as well as the theoretical background of the Landlab OverlandFlow component, based on a two-dimensional flood inundation model (LISFLOOD-FP: Bates and De Roo, 2000; Bates et al., 2010; de Almeida et al., 2012; de Almeida and Bates, 2013). This The description of the new OverlandFlow component includes information on how to set up a model domain using a digital elevation model, how to handle boundary conditionsand model data , how Landlab components store and share data in ‘fields’, and the validation against a known analytical solutionknown analytical solutions. The OverlandFlow component is then used to route nonsteady flow on one real landscape and two synthetic watersheds. The OverlandFlow component can be used to explore implications of a nonsteady hydrology method on short-term landscape evolution. Model output demonstrates that the OverlandFlow component is sensitive to both catchment characteristics and precipitation inputs. Output hydrographs can be flashier or broader depending on changes in these parameters and model domain. Finally, the variable discharge from the OverlandFlow component is coupled to a detachment-limited erosion component (DetachmentLtdErosion) to explore the feedbacks between hydrograph shape and short-term (10 year) erosion patterns throughout the landscape.

2 Landlab modeling framework

Landlab is a Python-language, open-source modeling framework, developed as a highly flexible and interdisciplinary library of tools that can be used to address scientific problems a range of hypotheses in Earth-surface dynamics (Adams et al., 2014; Tucker et al., 201 The utilities in Landlab allow users to build two-dimensional numerical models (Fig. 2). This includes a gridding engine that creates structured or unstructured grids, a set of pre-built components that implement code representing Earth surface or near-surface processes, and structures that handle data creation, management and sharing across the different process components. A diverse group of processes, such as uniform precipitation, detachment- and transport-limited sediment transport, crustal flexure, soil moisture, vegetation dynamics, and overland flow, are available in the Landlab library as process components.

The Landlab architecture allows for a “plug-and-play” style of model development, where process components can be coupled together. Coupled components share a grid instance and methods, and can operate on the data attached to the grid.

2.1 RasterModelGrid library

Landlab offers several different grid types. However, because the core algorithm in the OverlandFlow component can only be applied to ~~rectangular~~ structured grids, only the RasterModelGrid ~~(structured grid)~~ class is described here. The RasterModelGrid class can build both square (Δx = Δy)~~and rectilinear~~ , and rectangular ($\Delta x \neq \Delta y$) grids. OverlandFlow applications can only operate on square grid cells and require Δx = Δy. Each grid type in Landlab is composed of the same topological elements: nodes, which are points in (*x*, *y*) space; cells, a polygon with area $\Delta x \Delta y$ surrounding all non-perimeter or interior nodes; and links, ordered line segments which connect neighboring pairs of nodes and store directionality (Fig. 3). In the RasterModelGrid library, each node has four link neighbors, each oriented in a cardinal direction. Each node has two ~~“inlinks”~~‘inlinks’, connecting a given node to its south and west neighbors, and two ~~“outlinks”~~‘outlinks’, connecting to the neighbors in the north and east. The terms ~~“inlinks” and “outlinks”~~ ‘inlinks’ and ‘outlinks’ are for topological reference only, as the direction of fluxes in a typical Landlab component are calculated based on link gradients.

Model data ~~can be~~ are stored on these grid elements using Landlab data fields. The data fields are NumPy array structures that contain data associated with a given grid element. To store and access data on these fields, data ~~is~~ are assigned using a string keyword, and is accessed using Python’s mutable dictionary data structure. Data ~~is~~ are attached to the grid instance using these fields, and can be accessed using the string name keyword and updated by multiple Landlab components. For example, a field of values representing water depth at a grid node can be accessed using the following syntax: *grid.at_node[‘surface_water__depth’]*, where *grid* is the grid instance. Most Landlab names follow a simplified version of the naming conventions of the Community Surface Dynamics Modeling System (CSDMS), a set of standard names used by several models within the Earth science community ~~(Peckham, 2014)~~(Peckham, 2014; Hobley et al., 2017).

Model boundary conditions are set within a Landlab grid object. Boundary conditions are set on nodes and links (Fig. 4). Node boundary statuses can be set to either *boundary* or *core*. If a node is set to boundary, it can be further defined as an open, fixed gradient, or closed (no flux) boundary. In all RasterModelGrid instances, default boundary conditions are set as follows: perimeter nodes are open boundary nodes and interior nodes are core nodes. Boundary conditions can also be applied to interior nodes (e.g. NODATA values ~~in the interior of~~ on non-perimeter nodes in a digital elevation model can be set as closed boundaries). In OverlandFlow applications, open boundary nodes act as a watershed outlet, allowing water fluxes to move out of the model domain. Input rainfall is added to all core nodes, where water depths are updated at each time step to drive fluxes on grid links.

There are three link boundary statuses: active, inactive and fixed. Link boundary status is tied to the neighboring nodes. Once boundary conditions are set on the nodes, link boundary conditions are automatically updated. Active links occur where fluxes are calculated, and are found in two cases: (1) between two core nodes or (2) between one core node and one open boundary node. Fixed links can be assigned a fixed value that can be set or updated during the model run and are located between a fixed gradient node and a core node. Fluxes are not calculated on inactive links, which occur in two cases: (1) between a closed boundary and a core node or (2) between any pair of boundary nodes of any type (Fig. 4). Core nodes and active links make up the computational domain of a Landlab model.

3 Component equations

3.1 deAlmeida OverlandFlow component

Solving explicit 2D hydraulic formulations can be computationally challenging. For example, the one-dimensional shallow water equation includes four terms:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A_{xs}}\right) + gA_{xs}\frac{\partial (h+z)}{\partial x} + \frac{gn^2|Q|Q}{R^{4/3}A_{xs}} = 0 \quad (2)$$

where Q is water discharge $[L^3T^{-1}]$; t is time $[T]$; x is the location in space $[L]$; A_{xs} is cross-sectional area of the channel $[L^2]$; g is gravitational acceleration $[LT^{-2}]$; h is water depth $[L]$; z is the bed elevation $[L]$; n is the Manning's friction coefficient $[L^{-1/3}T]$ and R is the hydraulic radius $[L]$. These terms represent, from left to right, local acceleration, advection, fluid pressure and friction slope. To enhance stability, however, many solutions of the shallow water equations include numerical approximations that neglect terms from this solution. The simplest approximation, the kinematic wave model, neglects the local acceleration, advection and pressure terms. A more complex approximation, the diffusive wave model only neglects the local acceleration and advection terms (Kazezyılmaz-Alhan and Medina Jr, 2007).

The Landlab OverlandFlow component is based on the two-dimensional hydrodynamic algorithm developed for the LISFLOOD-FP model, and similar to the diffusive approximation, assumes a negligible contribution from the advection term of the shallow water equations (Bates et al., 2010; de Almeida et al., 2012). Additionally, this solution assumes a rectangular channel structure and constant flow width, impacting the pressure and friction terms (A_{xs} and R) in Eq. (2) (Bates et al., 2010). This formulation allows for a larger maximum time step than the more common diffusive approximation, enhancing the computational efficiency of the OverlandFlow component(Bates et al., 2010). de Almeida et al. (2012) further stabilized this algorithm by introducing a diffusive term into LISFLOOD-FP, updating the Bates et al. (2010) algorithm to work on lower friction surfaces without sacrificing computational speed.

To start the model, a stable time step is calculated. If a too-large time step is Stable time steps are set according to the Courant-Freidrichs-Levy criteria, which evaluates the ratio of time step size to grid resolution. If large time steps are used, areas of low slope are prone to wave oscillations, leading to a spatial 'checkerboard' pattern of water depths. Too-small time steps can have If time steps are very small, there may be significant impacts on the computational performance of a model. To maximize the trade-off between computational efficiency and stability of the de Almeida et al. (2012) solution, an adaptive time step (following Hunter et al., 2005) is used to keep the Courant-Freidrichs-Levy (CFL) CFL condition valid:

$$\Delta t_{max} = \alpha \frac{\Delta x}{\sqrt{gh_{max}}} \quad (3)$$

where Δt_{max} is the maximum time step that adheres to the CFL condition; α is a dimensionless stability coefficient less than 0.7; Δx is the grid resolution $[L]$; and $\sqrt{gh_{max}}$, the characteristic velocity of a shallow water wave, or the wave celerity

$[LT^{-1}]$, calculated using h_{max}, the maximum depth of water in the modeling domain $[L]$. When the OverlandFlow component is initialized, a thin film of water is set at all grid nodes to keep Eq. (3) valid. ~~Parameters and variables~~ Variables and parameters are defined in Tables (1) ~~,~~ and (2).

To calculate water discharge, de Almeida et al. (2012) derived an algorithm using the one-dimensional Saint-Venant or shallow water equations which ~~simulate~~ simulates a flood wave propagating across gridded terrain (for full derivation see deAlmeida et al., 2012). The explicit solution follows the form:

$$q_x^{t+\Delta t} = \frac{[\theta q_x^t + \frac{1-\theta}{2}(q_{(x-1)}^t + q_{(x+1)}^t)] - g h_{f(x)} \Delta t S_{w(x)}}{1 + g \Delta t n^2 |q_x^t| / h_f^{7/3}} \tag{4}$$

where q is water discharge per unit width $[L^2T^{-1}]$, calculated on links, here given superscript t for the current time step and subscript x describing the location of links in space (Fig. 5). θ is a weighting factor between 0 and 1, given a default value of 0.8, but can be tuned by the user. Setting θ to 1 returns the semi-implicit solution of Bates et al. (2010), that is, removing the diffusive effects implemented by de Almeida et al. (2012). g is gravitational acceleration $[LT^{-2}]$; h_f is the local maximum water surface elevation at a given time $[L]$; Δt is the adaptive time step $[T]$ (Eq. 3); S_w is the dimensionless water surface slope; and n is the Manning's friction coefficient $[L^{-1/3}T]$ (Tables 1 and 2). Equation (4) is calculated as two one-dimensional solutions in a D4 (four-direction) scheme: first calculated in the east-west direction (in the x direction) and then in the north-south direction (replacing x with y in Eq. 4).

Water depth is calculated on nodes, and updated at each time step as a function of the surrounding volumetric water fluxes on both horizontal and vertical links:

$$\frac{\Delta h}{\Delta t} = \frac{Q_{h(in)} - Q_{h(out)}}{\Delta x \Delta y} \tag{5}$$

where $Q_{h(in)}$ $[L^3T^{-1}]$ are the summed water discharges moving into a given node and $Q_{h(out)}$ are summed water discharges moving out of a given node, following Fig. (3). Directionality of discharge is determined not by the orientation of ~~"inlinks" or "outlinks"~~ 'inlinks' or 'outlinks', but instead, flow directions are determined by the gradient of each link. In this method, water mass is conserved, as the flow moving out of a node is balanced by the flow moving into the nearest node neighbor.

By default, this model assumes that all rainfall is spatially uniform and temporally constant, and all rainfall is converted to surface runoff. No infiltration or subsurface flow is considered within the model equations. Spatially or temporally variable rainfall can be set manually by the user in a driver file. Effective rainfall depths are applied over the basin and added to the surface water depths at each time step.

3.1.1 Steep environment stability criteria

The de Almeida et al. (2012) equation is designed for urban flooding events and is most stable in ~~flat~~ low-to-zero slope environments. To adjust this component to work in steep mountain catchments, extra stability criteria were added to keep ~~the simulation numerically stable~~ simulations numerically stable, using the *steep_slopes* keyword flag. A similar criterion was implemented in the CAESAR-Lisflood model (Coulthard et al., 2013). This method reduces the calculated flow discharge as needed to keep flow regime critical to subcritical using the Froude number (Eq. 6), where subcritical flow is defined as Fr ≤ 1.0. The Froude number is calculated as a function of wave velocity (u, calculated as $\frac{q}{h_f}$ on all links) and wave celerity ($\sqrt{gh_f}$):

$$Fr = \frac{u}{\sqrt{gh_f}} \tag{6}$$

If the $steep\_slopes$ flag is set when initializing OverlandFlow, restrictions are imposed to keep flow conditions critical to subcritical, a reasonable assumption for steep, mountain catchments (Grant, 1997). Specifically, if the water velocity calculated by the component drives the Froude number > 1.0, water velocity is reduced to a value that maintains a Froude number ≤ 1.0 for that given time step. This prevents water from draining too quickly and creating oscillating flow depths in steep reaches.

3.2 DetachmentLtdErosion component

To illustrate the flexibility of the OverlandFlow component, we present an example in Section 7, in which water discharges driven by overland flow calculated by the OverlandFlow component are coupled with surface erosion. Specifically, we explore a case where incision rate is solved explicitly, and depends on local water discharge and water surface gradient (e.g. Howard, 1994; Whipple and Tucker, 1999, 2002; Pelletier, 2004). This equation follows the form:

$$I = KQ^{m_{sp}}(S_{w_{max}})^{n_{sp}} - \beta \tag{7}$$

where I is the local incision rate $[LT^{-1}]$; K is a dimensional erodibility coefficient, units depend on the positive, dimensionless stream power coefficients m_{sp} and n_{sp}; Q is total water discharge on a node at a given time step $[L^3T^{-1}]$; $S_{w_{max}}$ is the local maximum water surface slope, which is dimensionless, and β is the optional threshold, below which no change in bed elevation is permitted $[LT^{-1}]$ (Tables 1 and 2). β is commonly interpreted as an entrainment threshold for bedload at rest on the bed in between erosional events (e.g. Attal et al., 2011). By default, m_{sp} and n_{sp} have set values of m_{sp} = 0.5 and n_{sp} = 1.0 that can be adjusted by the model user.

This solution allows for only the local detachment of material and assumes that transport rate is much larger than sediment supply rate. Therefore, no deposition is considered here. This erosion formulation is implemented with the Landlab DetachmentLtdErosion component. A threshold can be applied, under which no erosion is able to occuroccurs. For simplicity, no threshold is assumed here.

4 OverlandFlow model implementation in Landlab

To use the coupled Landlab OverlandFlow and DetachmentLtdErosion model, the user interacts with a driver file (Fig. 2). A simple Landlab driver file can run a model using fewer than 20 lines of code (Algorithm 1). There are four parts to running the coupled OverlandFlow-DetachmentLtdErosion model: (1) creating a domain using the RasterModelGrid, either explicitly or using a digital elevation model (DEM) in the ArcGIS ASCII format; (2) setting boundary conditions on the domain; (3) initializing the components; and (4) coupling them using the Landlab field data structures.

4.1 Initializing a grid: user-defined or DEM

To set up a grid instance, the user can create a rectangular grid by passing the number of rows, number of columns and grid resolution (Δx) as keywords to the RasterModelGrid object. This can be accomplished in one line of code: $grid = RasterModelGrid((number\_of\_node\_rows, number\_of\_node\_columns), \Delta x)$. In this method, only an empty instance of the grid is created, so elevation data must be assigned to grid nodes by the user.

An alternative method is to read in gridded terrain data from other file types. The original intent of Bates et al. (2010) was to develop a new flood inundation algorithm that can work easily with the growing availability of terrain data collected by satellite, airborne, or terrestrial sensors. Landlab's input and output utilities simplify this process by including include functionality to read in data from an ASCII file in the Esri ArcGIS format (Algorithm 1, Line 3). In this method, elevation data is are read in and automatically assigned to a Landlab data field called $topographic\_\_elevation$, set using the *name* keyword.

4.2 Boundary condition handling

Node boundary conditions are set throughout the grid in a Landlab OverlandFlow model to delineate the modeling domain (Algorithm 1, Line 4). For flow to move out of a watershed or system, an open boundary must be set at the outlet(s). If the node location of the outlet is unknown, there is a utility within the grid ($set\_watershed\_boundary\_condition$, Algorithm 1, Line 4) that will find the a single outlet and set it as an open boundary, in addition to setting all NODATA nodes to closed boundaries across the DEM or model domain. For landscapes with multiple potential outlets, such as urban environments, which are not discussed here, the user would have to manually identify and set nodes to open boundaries.

The de Almeida et al. (2012) equation uses neighboring link values when calculating water discharge (Fig. 5). By default, the edge of the watershed links are set to inactive status, and are assigned a value of 0, simulating no input from outside of the watershed for the simulation. If the user wants to simulate an input discharge on these links, an alternative method is the $set\_nodata\_nodes\_to\_fixed\_gradient$ method. If this method is called, the user can manually update discharge values on links with FIXED_LINK boundary status outside of the OverlandFlow class. Fixed links are accessed through their IDs using the RasterModelGrid class ($grid.fixed\_links$). In this method, the user can set a discharge value per unit width $[L^2T^{-1}]$ on all fixed links. This method is advised if the user has a known input discharge they want to force at the watershed or domain edge.

4.3 Initialize OverlandFlow and DetachmentLtdErosion

Landlab components have a standard initialization signature and take the grid instance as the first keyword (Algorithm 1, Lines 6-8). Any default parameters are also in the component signature and can be updated when the component is called. These parameters can be adjusted according to the physical nature of the landscape being tested. For the OverlandFlow component, Eq. (4) parameters Manning's n and discharge weighting factor θ can be adjusted. To keep the time step equation (Eq. 3) valid, an initial thin film of water is set across the model domain using the keyword h_init (Table 2). A steady, uniform precipitation rate can also be passed as a system input using the $rainfall\_intensity$ parameter (Algorithm 1, Line 7). Additionally, a stability criterion flag for steep catchments can be set ($steep\_slopes$ = TRUE, as described in Section 3.1.1.). In the DetachmentLtdErosion component, stream power exponents m_{sp} and n_{sp} and erodibility parameter K are also set by passing arguments to the component on instantiation.

4.4 Coupling using Landlab fields

To couple the OverlandFlow and DetachmentLtdErosion components, values for water discharge (Q_h), ~~surface water~~ water surface slope (S_w) and topographic elevation (z) are shared as data fields through the RasterModelGrid instance (e.g. Algorithm 1, Lines 14-15). At each time step, the water discharge and surface water slope fields are updated by the OverlandFlow component (Eq. 4). These new values are used to calculate an incision rate in the DetachmentLtdErosion component (Eq. 7). At each grid location, topographic elevation (z) is reduced according to the incision rate. Changes in topographic slope caused by erosion throughout the landscape will drive changes in surface water slope ($S_{w_{max}}$) and discharge (Q_h) in the next iteration of the OverlandFlow component.

5 Analytical solution

To validate the OverlandFlow component, we compared model output against an analytical solution for wave propagation on a flat surface, following Hunter et al. (2005). This test case propagates a wave over a flat horizontal surface (~~assuming~~ with a slope of 0), given a uniform friction coefficient (n) and constant, single-direction velocity (u). (For full derivation see: Hunter et al., 2005; Bates et al., 2010; de Almeida et al., 2012)~~, This solution iswritten as~~. The analytical solution is:

$$h(x,t) = \left[-\frac{7}{3}\left(n^2 u^2 \{x - ut\}\right)\right]^{\frac{3}{7}} \tag{8}$$

Solving for the leftmost boundary of the modeling domain ($x = 0$) gives:

$$h(0,t) = \left(\frac{7}{3} n^2 u^3 t\right)^{\frac{3}{7}} \tag{9}$$

~~To test the Landlab OverlandFlow component, a~~ All analytical solution tests were modeled across a rectangular RasterModelGrid instance with dimensions of ~~32 rows by 240 columns was initialized with a resolution of $\Delta x = \Delta y = 25$~~ 800 m by 6000 m. The water depth boundary condition through time (Eq. 9) is applied to the left edge of the domain, ~~while~~ whereas the top, right and bottom edges of the grid are set to CLOSED_BOUNDARY status to keep flow moving uniformly to the east and contained within the computational domain. All input flow remains on the surface of the domain, as no infiltration is considered. Grid set up and test parameters are described in Table (3).

5.1 Sensitivity to grid resolution

~~Two analytical solutiontest~~ Following Bates et al. (2010), the behavior of OverlandFlow was modeled across a range of grid resolutions. Velocity and surface roughness were held constant throughout all runs (n = 0.03 sm$^{-1/3}$, and u = 1.0 ms^{-1}) and

θ was set to 1.0 (Bates et al., 2010, Fig. 2). Wave fronts were plotted at model time t = 3600 s. Four grid resolutions were tested: Δx = 5 m, 10 m, 25 m and 50 m. These tests envelop a range of resolutions, including the 10 m and 30 m dataset resolutions of the United States Geological Survey National Elevation Dataset (USGS-NED) as well as 30 m datasets from the European Environmental Agency's Digital Elevation Model over Europe (EU-DEM). Larger grid resolutions (Δx > 50 m) are not shown here, as at those coarser grid resolutions, the OverlandFlow component becomes sensitive to the initial thin film of water (h_init) that is used to keep the timestep (Eq. 3) valid. h_init was set to 1 mm in all test cases described here.

The minimum time step for the Δx = 50 m test case can be compared to the published value of Bates et al. (2010). Time steps will decrease with increasing water depth, per Eq. (3). The minimum time step from the OverlandFlow component tests, sampled at t = 3600 s was 7.25 s, identical to the value provided by Bates et al. (2010).

In all grid resolution tests, the OverlandFlow predicted wave fronts closely approximate the analytical solution, which was plotted for the Δx = 50 m test case (Fig. 6a). At the front of the wave, the predicted water elevations from OverlandFlow better approximate the analytical solution as grid resolution increases (Fig. 6b), as noted by Bates et al. (2010) for the semi-implicit (θ = 1.0) solution in LISFLOOD-FP. Figure 6 demonstrates that, with only a minor sensitivity at the leading edge of the wave front, the Landlab OverlandFlow model can effectively operate on a wide range of grid resolutions.

5.2 Sensitivity to surface roughness

To test the Landlab OverlandFlow component with different roughness and resolution characteristics, a RasterModelGrid instance with dimensions of 32 rows by 240 columns was initialized with a resolution of Δx = 25 m. In order to evaluate the sensitivity to surface roughness (Manning's n), two analytical solution test cases were run on the domain. The first is a low friction test ($n = 0.01$ sm$^{-1/3}$, $u = 0.4$ ms^{-1}, Fig. 7a,c) following the solution of ~~Bates et al. (2010); de Almeida et al. (2012, Fig. 2)~~Bates et al. and de Almeida et al. (2012, Fig.2). In the second test, the friction value ~~is~~ was increased by an order of magnitude~~to closer approximate Manning's n values found in natural landscapes~~, while velocity was unchanged (n = 0.1 sm$^{-1/3}$, u = 0.4 ms^{-1}, Fig. 7b,d). The two Manning's n values in this test were selected to demonstrate model behavior across a range of conditions: n = 0.01 sm$^{-1/3}$ represents urban environments or man-made channel systems; n = 0.1 sm$^{-1/3}$ can be used in landscapes or channels characterized by dense brush and tree growth (Chow, 1959). To mirror previous tests using the LISFLOOD-FP model, Fig. (7) shows the water depth of wave fronts at three model times: t = 2700, 5400 and 9000 s. Each dashed line represents a changing theta value in Eq. (4), with θ = 1.0 representing the semi-implicit solution ~~from Bates et al. (2010).~~ of Bates et al. (2010).

The minimum time step for the low friction test case (n = 0.01 sm$^{-1/3}$) can be compared to the published value of de Almeida et al. (2012). The minimum time step from the OverlandFlow component tests, sampled at t = 9000 s was 8.6 s, identical to the value provided by de Almeida et al. (2012).

In all velocity-roughness conditions, the wave fronts predicted by the Landlab OverlandFlow component correlate well with the analytical solution defined using Eq. (9). In the low friction case (n = 0.01, Fig. 7a,c), the wave speed produced using ~~the~~ Landlab OverlandFlow is slower than the predicted wave front speed. Increasing surface roughness (n = 0.1, Fig. 7b,d), leads to the predicted wave front overestimating the analytical solution. Overall, the close approximation of the modeled solutions to known analytical solutions, across a wide range of roughness values, demonstrate the ~~efficacy~~ sensitivity of the Landlab OverlandFlow component ~~.~~ to different roughness coefficients, and the flexibility of the component to work across a wide range of landscape conditions.

6 Application: Modeling OverlandFlow in a real landscape

6.1 ~~Background~~

~~Most rainfall-runoff models are applied over real landscapes to simulate hydrologic events. Most rainfall-runoff models can be classified as either lumped or distributed. Lumped rainfall-runoff models represent watersheds as characteristic subareas or subbasins, and do not account for spatial variability in subbasin parameters. These models assume that average variables and parameters adequately capture the processes being observed (Moradkhani and Sorooshian, 2009; Beven, 2011; Devi et al., 2015). Some examples of lumped hydrologic models include: Hydrological Simulation Program–Fortran (HSPF Donigan et al., 1984) and HEC-HMS (Scharffenberg and Fleming, 2006). Alternatively, distributed rainfall-runoff model domains are broken into smaller, discrete elements or grid cells. Distributed models allow for spatial variability in model parameters or state variables. Existing distributed models include TOPMODEL, (Beven and Kirkby, 1979), KINEROS2 (Woolhiser et al., 1990), GSSHA (Downer and Ogden, 20 and tRibs (Ivanov et al., 2004). Like these models, the~~ The Landlab OverlandFlow component can be used as a distributed rainfall-runoff model, routing ~~rainfall~~ precipitation across a real landscape DEM and estimating runoff for every point within a discrete RasterModelGrid instance. Discharge values ~~are~~ can be calculated at every point in the watershed and updated at each timestep. Updated water depths, driven by changing discharge, can be used to calculate shear stress following the depth-slope product:

$$\tau = \rho g h S_w \tag{10}$$

Equation 10 calculates the bed shear stress τ $[ML^{-1}T^{-2}]$ as a function of fluid density (ρ) $[ML^{-3}]$, g, gravity; h, water depth; and S_w surface water slope. Shear stress exerted on the bed can be used to estimate sediment transport driven by flowing water throughout the domain.

Here we illustrate a single storm routed across a DEM. In addition to water discharge, water depth and bed shear stress are calculated by the model~~, and plotted at the peak of the outlet storm hydrograph~~. This implementation of the OverlandFlow component illustrates how hydrologists can use Landlab as a simplified distributed rainfall-runoff model to ~~predict~~ estimate the hydrologic and sedimentologic impact of a single storm on a real landscape. ~~These results demonstrate how the model can be used to predict flooding and erosion events.~~

6.1 Methods: domain and parameterization

To apply the OverlandFlow component as a rainfall-runoff model, a DEM can be read into Landlab and converted easily into a RasterModelGrid instance. ~~For~~ The Spring Creek watershed is used in this example, ~~the Spring Creek watershed is used~~ as a pre-processed DEM for the watershed has been used before in Landlab applications (e.g. Adams et al., 2016; Hobley et al., 2017, Fig. 15).

Spring Creek is a steep, 27 km^2 watershed, located within Pike National Forest in central Colorado, USA (Fig. 8a). This LiDAR-derived DEM has square cells with a resolution of $\Delta x =$ ~~$\Delta y =$~~ 30 m (DEM data: Tucker, 2010). Using the *set_watershed_boundar* utility, all NODATA nodes in the DEM are set to ~~CLOSED_BOUNDARY~~ closed boundary status (Algorithm 1, Line 4). This method identifies the lowest elevation point ~~within the~~ along the edge of the watershed, the outlet, and sets it to an ~~OPEN_BOUNDARY~~open boundary.

The DEM was pre-processed ~~and pit-filled in~~ using the Landlab SinkFiller component is used to ensure all flow can be removed from the domain. This component fills pits in the DEM in a D4 routing scheme, where all nodes have at least one downstream neighbor in one of the four cardinal directions (Algorithm 1, Lines 8-9). ~~This step ensures all flow can be removed from the domain.~~ If this step were to be skipped, flow may pond in “lakes” or “pits" in the domain, where flow cannot travel out of a given node location until the water surface elevation of the lake exceeds the bed elevation of the ~~D4~~ four neighboring nodes.

To initiate flow across the domain, a single storm was routed across the watershed. ~~The~~ A theoretical ‘base storm’ (Table 4) was used as an example, with ~~an~~ a constant, effective rainfall rate of 5 mm hr^{-1} and a duration of 2 hr. The storm event was spatially uniform across the domain, and the 10 mm total rainfall depth was estimated using NOAA precipitation data from a nearby site in Colorado (NOAA, 2014). For this storm, hydrographs were recorded at three points ~~throughout the watershed. At the peak of the outlet hydrograph, water depth~~ within the model domain. No infiltration or subsurface flow was considered in this test case. Water depths at every location in the watershed ~~was~~ were used to calculate the shear stress, which can be used to make interpretations about the transport of sediment across the watershed as a result of the storm.

6.2 Results and implications

In order to illustrate the downstream movement of the flood wave, hydrographs were plotted at three locations within the ~~watershed~~ channel for the duration of the flow event. The three hydrographs correspond to the three starred locations on the watershed DEM in Fig. ~~8a~~(8a): at the outlet (black line, Fig. 8b), the approximate midpoint of the main channel (violet line, Fig. 8b) and an upstream location in the main channel (lavender line, Fig. 8b). In these hydrographs, ~~both~~ peak discharge and time to peak increase as the sampling site nears the outlet (moving from lighter to darker color). This ~~pattern is~~ demonstrates the model behaving as expected as water accumulates in the main channel from the tributaries. ~~Upstream points have less contributing area, and so less water passes through those locations. The peak in the upstream-most hydrograph occurs first, as the flood wave passes through that location before propagating downstream. Downstream, the outlet has the largest contributing area in the watershed. Because the flow path is longest from the upstream reaches to the outlet, the time to peak is greater than upstream hydrographs. The outlet hydrograph is driven by contributing flow from all upstream points, increasing the peak discharge value.~~

Water depths are variable at each point throughout the model run, changing as a function of discharge inputs, outputs and effective rainfall rate at each time step (Eq. 5). Water depth values can be mapped across the domain at discrete time steps. In this example, water depth was plotted at the peak of the outlet hydrograph (Fig. 8c). ~~At this peak, there is still water in the domain ready to flow out as part of the rising limb. These water~~ Water depths can be used to calculate shear stress (following

Eq. 10)~~, also plotted at the peak of the outlet hydrograph (Fig. ~~. Stress values were tracked at all points throughout the model run, and the local maximum value for each node was plotted in Fig. (8d). Shear stress (τ) values can be used to interpret the size of particles that can be entrained and transported by channelized flow. Greater τ values correspond to areas with greater water depths (e.g. channels), where more sediment transport would be expected in high flow conditions.

In this example, we illustrate ~~the flow of~~ hydrographs across a real landscape, and the resulting shear stress values. These results can be used to explore the processes controlling overland flow in a gauged landscape. Shear stress values can be used to estimate sediment transport rates, and make interpretations about spatial patterns of erosion and deposition, as well as total sediment yields for particular storm events. These values could be calibrated in order to explore landscape sensitivity to rainfall-runoff events.

7 Application: Long-term fluvial erosion in Landlab

7.1 ~~Background~~

~~Most landscape evolution models simplify hydrology by assuming steady-state, calculated as:~~

$$Q_{ss} = PA$$

~~where Q_{ss} is the steady-state water discharge L^3T^{-1}, P is a constant effective precipitation or runoff rate $LT^{-1}$and A is drainage area L^2. Discharge is steady for the duration of a precipitation event and stops when precipitation ends. Figure 1 compares this steady-state hydrology assumption against the physically-based nonsteady method at one location in a watershed. The effective rainfall rate P is the same rate and has the same duration for both the steady (Q_{ss}) and nonsteady (Q_h) discharge simulations. The nonsteady hydrograph (Q_h) lasts longer through time than steady-state discharge (Q_{ss}). If a constant, effective precipitation rate is applied for long enough in the model, the OverlandFlow results will eventually reach this steady discharge value predicted by Eq. (1).~~

The ~~steady-state hydrology assumption can be problematic when applied to physical systems. Steady-state hydrology is reached when precipitation falls over the entire watershed for long enough duration that water from the furthest upstream point has enough travel time to reach the outlet. This condition will not be met when storms are very short, watersheds have a large drainage area, or both. Under these conditions, predicted steady-state discharge may not be reached in a watershed. The~~ implementation of the OverlandFlow component in Landlab allows us to investigate the impact of storm characteristics on the resulting hydrograph and how these hydrographs drive erosion processes throughout the ~~watershed~~basin. Here, we demonstrate the abilities of this new component and how the component resolves the ~~detail~~ details of the storm ~~hydrographs, comparing them~~ hydrograph, and how these hydrographs compare to the traditional ~~landscape evolution hydrology methods~~steady-state method used in landscape evolution models. Additionally, in coupling this new component with the Landlab DetachmentLtdErosion component, these model results ~~can~~ illustrate the erosion magnitudes and patterns in response to ~~that~~ a hydrograph, and allow us to make inferences about how this type of hydrodynamic model could impact ~~longer term~~ long-term geomorphic evolution of similar watersheds.

7.1 Methods: domain and parameterization

To test the new Landlab OverlandFlow component, two synthetic watersheds were generated using the Landlab FlowRouter and StreamPowerEroder components ~~(not described here, see Hobley et al., 2017, in review)~~(not described here, see Hobley et al., 2017). These basins were evolved to topographic, or geomorphic, steady state, where rock uplift is matched by erosion at all grid locations, and topography is effectively unchanging through time. Two watershed shapes were modeled: a 'square' watershed (Fig. 9a) and a 'long' watershed (Fig. 9b) to evaluate if hydrograph shapes change with increasing maximum flow length, where the 'long' basin has longer flow paths to the outlet when compared to the 'square'. Each watershed has a drainage area of approximately 36 km^2 at the outlet. The square basin has dimensions of 200 rows by 200 columns; the long basin has dimensions of 400 rows by 100 columns. Cells are square and have a resolution of Δx = ~~Δy =~~ 30 m. Each basin has an ~~OPEN_BOUNDARY for~~ open boundary at the watershed outlet, located at the center node of the southernmost grid edge. The remaining southern nodes, along with the west, east and north grid edges, were set to ~~CLOSED_BOUNDARY~~ closed boundary status.

To initiate flow and incision, three precipitation events were modeled across both watersheds. These storms were represented as spatially uniform across the model domain, and intensities were constant for the given storm duration. No infiltration or subsurface flow was modeled in these test cases. The base storm, following the example in the real landscape, has a rainfall intensity of 5 mm hr^{-1} falling over 2 hr. To test the impacts of changing intensity and duration on model output, duration was extended compared to the base case (the 'longer duration' storm, Table 4) and intensity was increased relative to the base storm (the 'higher intensity' storm, Table 4). The storm with the longer duration maintained the 5 mm hr^{-1} rainfall intensity, but duration was doubled to 4 hr. In the higher intensity storm, rainfall rate was doubled to 10 mm hr^{-1}, while the base duration of 2 hr was kept.

Discharge was recorded at all ~~points throughout the watershed~~ grid locations for each model run. To capture the entire overland flow event, all simulations were run for ~~at least~~ 24 modeled hours. A single 'base' storm on the square watershed run for 24 modeled hours took approximately 80 seconds on a 2014 iMac with 4 GHz Intel Core i7 processors.

The OverlandFlow results from the two test basins (Fig. 9) were coupled with the DetachmentLtdErosion component in Landlab to test the impact of nonsteady hydrology on erosional patterns. At each time step, the DetachmentLtdErosion component calculated total incision depth using Eq. (7). Cumulative incision depth at the end of each modeled run was saved for all grid locations. Both test basins were evolved to topographic steady-state, and so the predicted geomorphic 'steady-state' incision rate is equal to the rock uplift rate ~~used in the StreamPowerEroder component~~applied in the model. Total incised depth for the hydrologic steady-state runs can be inferred from this steady-state incision rate. To test the erosional impact of non-steady hydrology, short-term landscape evolution simulations were run on each basin, for the three precipitation events (Table 4). The known steady-state incision rate and depth can be compared to the predicted DetachmentLtdErosion depth produced when coupled with the OverlandFlow component. In each basin, an annual precipitation rate of 0.5 m yr^{-1} was set, and each simulation was run for 10 model years. Decadal-scale runs were selected as they can be run quickly on a personal machine (on the order of hours), and the results can be used to make inferences about how erosion patterns would scale in long-term landscape evolution runs. Because of differences in intensity and duration, the base storm was run 500 times, assuming 50 storms per modeled year, while the longer duration and high intensity storms were run 250 times, assuming 25 storms per modeled year, to achieve 5 m total rainfall depth over 10 years. For each model run, total incised depth was saved at all grid locations.

7.2 Results and implications

The hydrograph measured at the outlet of both the square and long basins are compared with the steady-state hydrographs (Fig. 10). The gray box represents the steady-state case, which produces the same discharge in both watersheds, as they have the same drainage area. In the nonsteady method, hydrograph shapes are distinct between the different basins. In both test basin results from the base case storm (Table 4), the hydrographs persist after precipitation and steady-state discharge end. In the case of the square basin, peak discharge exceeds that predicted by the steady-state case (~ 50 m^3/s), a signal not seen in the long basin results. In the long basin, a singular peak discharge is not clear, and discharge values represented by the hydrograph are less than the predicted steady-state at all timesteps. Because flow in the long basin has to travel a greater distance from the upstream portion of the watershed, there is an elongated hydrograph with no clear peak discharge.

As expected, the OverlandFlow component is also sensitive to changes in rainfall characteristics in both test basins. In the square basin, extending the duration of the storm (green line, Fig. 10b) results in a higher overall peak discharge when compared to the base storm (light blue line, Fig. 10b), as well as a longer overall hydrograph. The second peak in the longer duration hydrograph is due to the drainage organization in the square basin (Fig. 9a), when flow from other tributaries reaches the outlet after the initial flood peak (see supplemental video). Increasing the rainfall intensity in the square basin (dark blue line, Fig. 10c) increases peak discharge when compared to the base storm case.

In the square basin, each storm has a clear hydrograph signature. These patterns are distinct from the long basin results. In the long basin, all three storm hydrographs have lower discharges than similar storms in the square basin ~~, reflecting the patterns from the basin comparison plot~~ (Fig. 10a). The higher intensity storm run (mauve line, Fig. 10e), has higher discharge values than both the base case and longer duration runs (Fig. 10d), similar to what was seen in the square basin. However, the hydrograph shapes and discharge values are largely similar in all long basin cases, with longer, lower ~~hydrograph shapes~~ hydrographs that reflect the longer travel time of water in the basin.

After the modeled 10 years, the total incised depths for the three storm cases can be compared to predicted geomorphic steady-state incised depths. The nonsteady incision depth results also demonstrate distinct patterns when compared to ~~the value predicted by~~ geomorphic steady-state. Figure 11 shows that the coupled steady-state hydrology and stream power solutions predict higher incision rates than the nonsteady method at all drainage areas. These patterns are clear in both the long watershed with a broad hydrograph, and the square basin with a more peaked hydrograph. The depth of total incision in both basins are on the same order of magnitude, and the pattern of increasing incision depth moving downstream is also similar in both basins (Fig. 11a). While the steady-state topography maintains the same land surface elevation, changing the hydrologic regime to nonsteady would lead to more relief in modeled landscapes, as the downstream will initially erode more rapidly than the upstream channels. In other words, the upstream locations will need to steepen more than the downstream locations in order to reach geomorphic steady-state incision rates ~~at all locations in~~ throughout the landscape. Because the upstream locations must steepen more than the downstream locations in order to reach that geomorphic steady-state, this will also lead to increased channel concavity on landscape evolution timescales.

The pattern of increasing downstream erosion is seen in all storm cases (Figs. 11b,c; Table 4). In both basins, total eroded depth is least in the higher intensity storm, increases in the longer duration storm, and is greatest in the base case. The higher intensity storm exhibits a greater peak discharge, but there are fewer overall higher intensity and longer duration storms when compared to the base storm case to maintain the 5 m total rainfall depth over 10 years. Additionally, when calculating total incision using the stream power model, increases in discharge are less significant than the water surface slope due to the exponents m and n. While not explored here, changing the stream power exponents m and n will likely impact the steady and nonsteady fluvial erosion results in this model.

Overall, these results suggest that when compared to the OverlandFlow component, hydrologic steady-state predictions can over- or underestimate the peak of a hydrograph depending on basin orientation or shape (Fig. 10a). ~~Additionally~~As expected, the hydrodynamic algorithm from de Almeida et al. (2012) is sensitive to rainfall inputs, both with changes in duration and intensity (Figs. 10b-e). This component can be applied across a range of time scales, used for predictions of overland flow for a single storm or multiple storms, and used efficiently with other process components in Landlab, as demonstrated by coupling to the DetachmentLtdErosion component.

The patterns of erosion support earlier findings by Sólyom and Tucker (2004), which suggested that landscapes dominated by nonsteady runoff patterns can be characterized by greater overall relief. Their results were generated using an incision rate controlled by the peak discharge. While the runs using the Landlab model were over shorter timescales, these results were integrated over the entirety of the hydrograph, not just the peak discharge. These results suggest that on longer timescales, watershed morphology would vary depending on the method used to calculate overland flow. Additionally, as the watershed morphology evolves in response to these spatial variations in incision rate, the hydrograph shape may change, impacting overall incision patterns and rates. The difference in patterns between steady and nonsteady hydrology implies that the retention of water within the ~~watershed~~ channels during a runoff event, driven by nonsteady hydrology, can drive have morphological significance over longer-term landscape evolution.

8 Future applications

~~Post-wildfire hydrologic changes have been linked to large post-fire erosion events.~~ The Landlab OverlandFlow model ~~could be used to explore the processes driving post-fire flooding and erosion. For example, this model has been applied to explore trends in discharge and sediment yield in the Spring Creek watershed(Adams et al., 2016). To fully capture post-fire dynamics, this model can be coupled with other components , such as infiltration or~~ is flexible enough to be used in a number of scientific applications not discussed here. This manuscript makes no distinction between hillslope or channel processes, which can be problematic as hillslopes make up the majority of a watershed area and supply sediment to the channels. If coupled with a hillslope sheet-wash component, OverlandFlow could be used to examine how nonsteady channel processes interact with hillslope processes to sculpt watersheds across a range of spatial and temporal scales. Furthermore, these hillslope processes can be coupled with a fluvial transport-limited ~~sediment transport. In landscapes with extensive field data, both pre- and post-fire, the~~ component, and applied at event scales to explore sediment delivery from hillslopes to channels and how quickly sediment moves through a watershed. At landscape evolution timescales, evolved topographies resulting from more physically-based hydrology and sediment transport components can be compared to traditional models, to evaluate how physical parameters within the fluvial and hillslope models impact landscape relief and organization.

Other opportunities include evaluating the impact of spatially variable parameters on model behavior. Spatial variability in rainfall could be explored with the development of new components that model orography or variability in storm cell size. Following the work of Huang and Niemann (2014), the OverlandFlow model can be used to ~~understand potential post-fire responses to large storm events.~~ explore patterns in runoff and erosion in response to changes in storm size, area and location within a watershed. Spatially variable roughness could also be incorporated into the OverlandFlow component. A water-depth-dependent Manning's n method, similar to that of Rengers et al. (2016) could be implemented, where roughness at each grid node is calculated based on local water depths. Another method to evaluate spatial variability in roughness would be to allow the user to read-in or set a map of surface roughness based on field observations.

Another application ~~under exploration is a model created by coupling the Overland Flow component with~~ of the OverlandFlow component is coupling it to Landlab's ecohydrology components (Nudurupati et al., 2015). In this ~~model type , OverlandFlow can~~ type of application, OverlandFlow could be used to ~~drive water discharge and update water depths across the~~ calculate water depths across a surface. Surface water depths can be used to ~~simulate~~ drive infiltration in the SoilInfiltrationGreenAmpt component. The SoilMoisture component computes the water balance and root-zone soil moisture values. Soil moisture can drive changes in the Vegetation component, which simulates above-ground live and dead biomass. This coupled model ~~can be used~~ would provide a more complete process ecohydrology model, to be used in applications to understand how different flood events impact the succession of vegetation.

Finally, the applications explored in this manuscript are on shorter timescales, ranging from event- to decadal-scale runs. An interesting future direction is exploring the OverlandFlow component in true landscape evolution runs (millennia or longer). Preliminary work modeling 10^3 to ~~study how differences in steady- and nonsteady hydrology may drive vegetationevolution on annual to decadal timescales~~ 10^4 years demonstrates that patterns seen in the decadal applications are clear, however, the full implications of hydrograph-driven erosion on long time scales need to be further explored.

9 Conclusions

~~The OverlandFlow componentsuccessfully integrates a two-dimensional hydrodynamic algorithm into the Landlabmodeling framework~~This manuscript illustrates the theory behind the OverlandFlow component, and how to use it as part of Landlab. Being part of the Landlab modeling framework comes with many advantages. The OverlandFlow component can make use of DEM input and output utilities and be coupled with other Landlab components, ~~illustrated here as a~~ and is flexible enough to allow for a wide range of applications in both geomorphology and hydrology. As illustrated here, it can be used as a simplified distributed rainfall-runoff model. Those results demonstrate that the OverlandFlow component can be used to generate realistic hydrologic responses across a watershed DEM. This hydrology method can be used to estimate the grain sizes moved by different storm events, and in the future could be coupled with other components and calibrated to understand the hydrologic response to flooding events.

It also can be coupled to the stream power DetachmentLtdErosion component to explore decadal impacts of a hydrograph on erosion . The OverlandFlow component is also flexible enough to allow for future applications in both geomorphology and hydrology. This manuscript illustrates the theory in the OverlandFlow component in Landlab and how to use and couple the component to other Landlab components. on decadal scales. In the synthetic landscapes explored here, the hydrograph results from the OverlandFlow component demonstrate a sensitivity to both basin shape, precipitation duration and intensity. The erosion results predicted by using steady-state and nonsteady hydrology are distinct in both the patterns and magnitudes of eroded depth and incision rates. Incision driven by nonsteady hydrology showed increasing incision rates moving downstream in the modeled watersheds. These results suggest that nonsteady hydrology could have important implications for predicting watershed relief and hypsometry in landscapes with different rainfall regimes, and that choice of hydrology method can have implications for both short- and long-term landscape evolution modeling results.

10 Code availability

The Landlab OverlandFlow and DetachmentLtdErosion components are part of Landlab version 1.0.0. Source code for the Landlab project is housed on GitHub: http://github.com/landlab/landlab. Documentation, installation instructions and software dependencies for the entire Landlab project can be found at: http://landlab.github.io/. Driver scripts for the applications illustrated in this paper can be found at: https://github.com/landlab/pub_adams_etal_gmd (Adams, GitHub Repository). The Landlab project is tested on recent-generation Mac, Linux and Windows platforms using Python versions 2.7, 3.4, and 3.5. The Landlab modeling framework is distributed under a MIT open-source license.

Competing interests. The authors declare that they have no conflict of interest.

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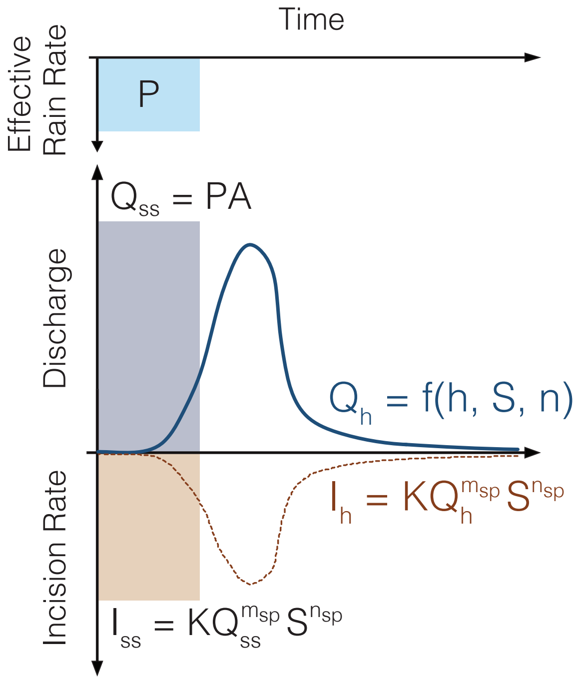

Figure 1. Cartoon illustrating the differences between steady-state and nonsteady hydrology and incision at a single point within a watershed. In this schematic, the effective precipitation rate P is the same for both steady and nonsteady cases. During the precipitation event, steady discharge Q_{ss} and incision rate I_{ss} are constant, driven by that effective precipitation rate and drainage area (A), erodibility (K), water surface slope (S) and stream power exponents (m_{sp}, n_{sp}). In the nonsteady case, a wave front begins to propagate and incise, producing time-varying discharge Q_h, calculated using physical parameters such as water depth (h), water surface slope (S) and Manning's roughness coefficient (n). Nonsteady incision rate I_h is calculated using the time-varying discharge, erodibility and water surface slope. At the end of the precipitation event, Q_{ss} and I_{ss} also end, while nonsteady values Q_h and I_h continue until all water has completely exited the system at the outlet.

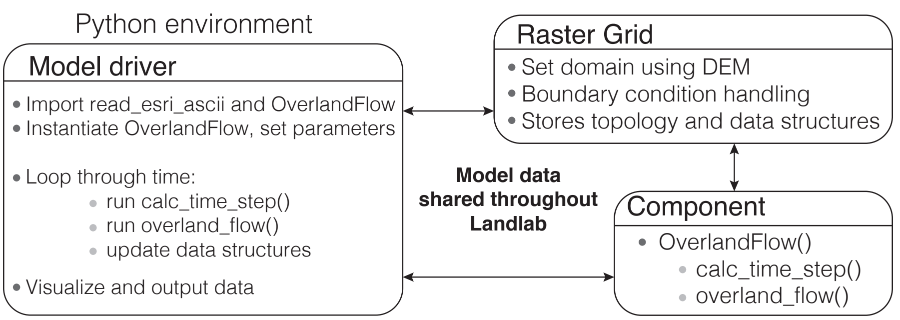

Figure 2. Sample workflow for the Landlab OverlandFlow component. Users create or ~~use~~ adapt a pre-developed model driver, where the grid, components and model utilities are imported and instantiated. The time loop is set in the driver, and at each time step the component methods are called and the data structures are updated.

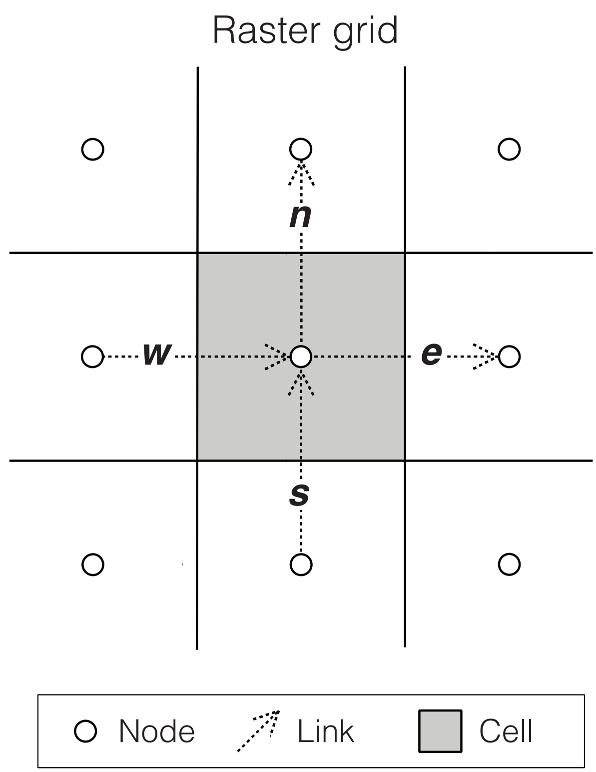

Figure 3. Example of the Landlab structured grid type with key topological elements shown. In the Landlab OverlandFlow component, RasterModelGrid class stores data at both nodes and links. Links denoted as west (w) and south (s) are called “‘inlinks”’, while north (n) and east (e) are “‘outlinks”’ of the center node. Direction is only for topological reference; flux directionality is tied to gradients on the grid.

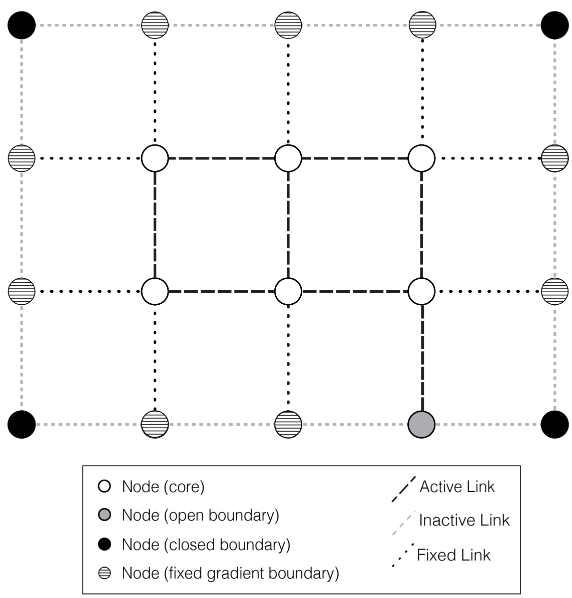

Figure 4. Simple example of Landlab RasterModelGrid, demonstrating both node and link boundary conditions. The OverlandFlow class calculates fluxes at active links, and can update the surrounding fixed links according to these fluxes. No fluxes are calculated at inactive links. Water depth is updated at core and open boundary nodes. No calculations are performed on closed or fixed gradient boundaries. Note that RasterModelGrid cell elements are not illustrated here.

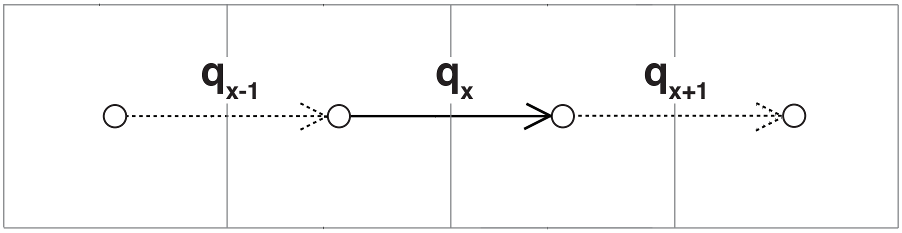

Figure 5. In the de Almeida et al. (2012) equation, flux information from neighboring links is used to calculate surface water discharge. In this sample one-dimensional grid, discharge is calculated in the horizontal (subscript x) direction on links. Here, discharge is calculated at location q_x using the left neighbor (q_{x-1}) and right neighbor (q_{x+1}) flux values, following Eq. (4).

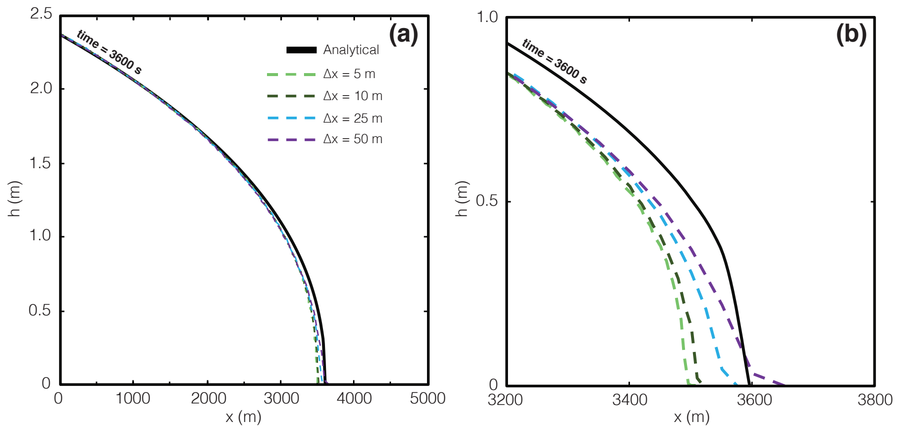

Figure 6. Sensitivity of the Landlab OverlandFlow component to changes in grid resolution, tested against the analytical solution. Panel **(a)** is illustrated in the same manner as Bates et al. (2010, Fig. 2), and shows water depths plotted against distance, modeled at four different grid resolutions, at t = 3600 s. Panel **(b)** is a zoomed-in image of all wave fronts from panel **(a)**.

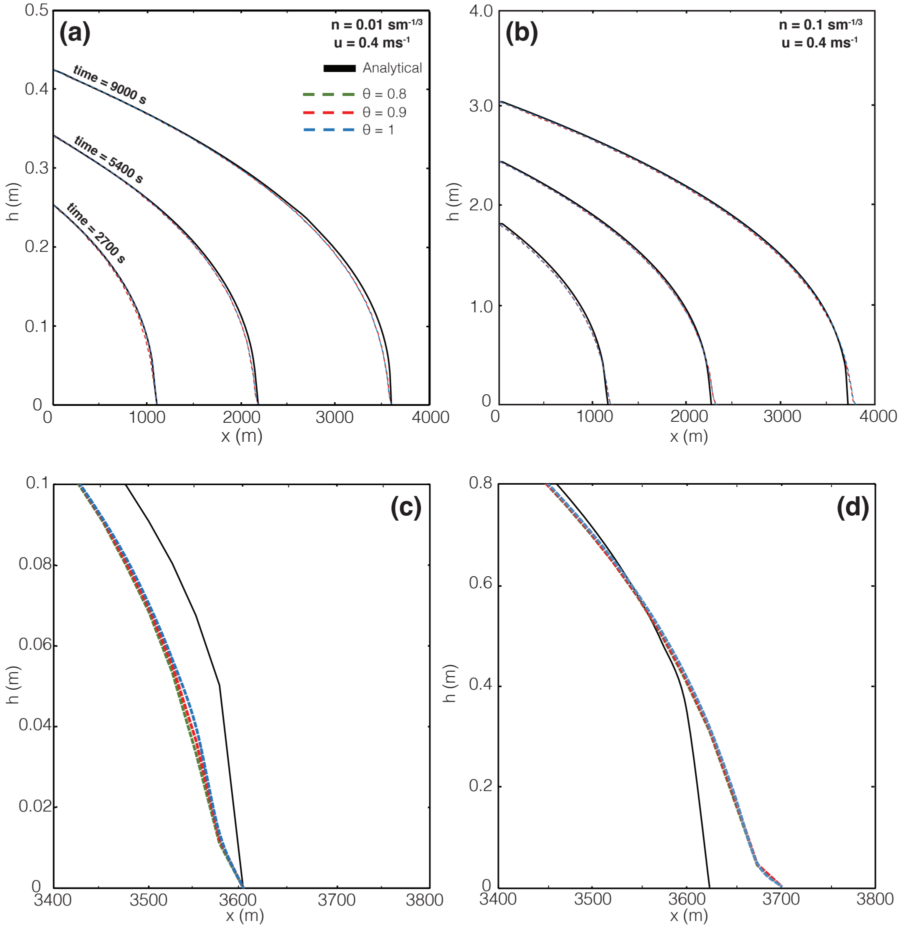

Figure 7. ~~Results from test~~ Sensitivity of ~~analytical solution using~~ the Landlab OverlandFlow component with changing Manning's n, compared to the analytical solution. This figure is illustrated in the same manner as Fig. (2) from de Almeida et al. (2012). Water depth was plotted against distance for two combinations of velocity and friction coefficient values. Both panels **(a)** and **(b)** show water depths for t = 2700, 5400, and 9000 s. Panels **(c)** and **(d)** are zoomed-in images of the wave ~~front~~ fronts from panels **(a)** and **(b)** respectively, at time = 9000 s.

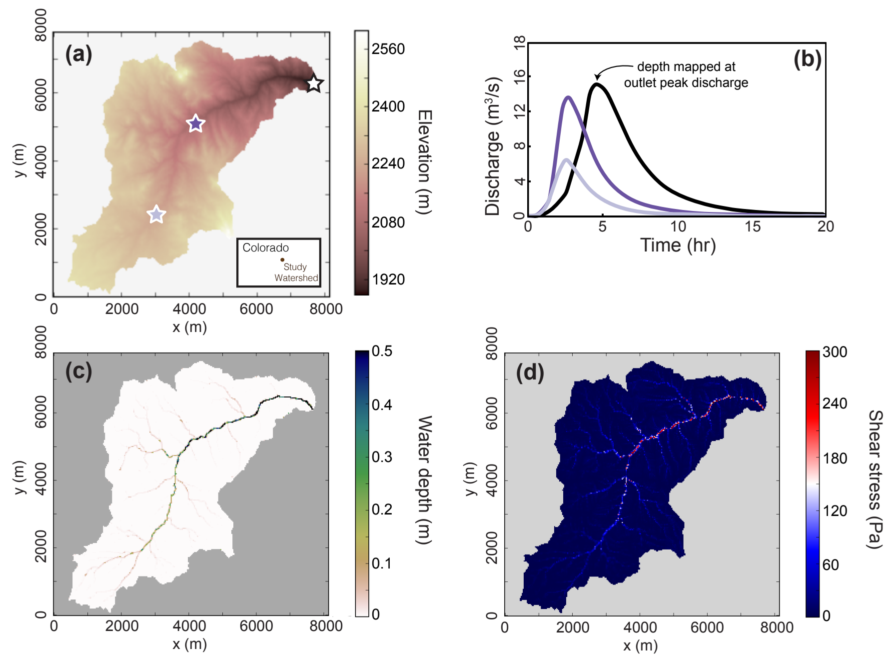

Figure 8. Results from the real landscape ~~application~~example. Panel **(a)** shows the topography of the Spring Creek watershed, and the inset notes the location of this watershed in central Colorado, USA. Panel **(b)** illustrates the hydrographs from three points within the ~~channels~~main channel. The location for each hydrograph sampling site is shown in panel **(a)**, with the lightest color at the upstream, darkening in color towards the outlet. The delay in hydrograph peak is clearest between the outlet and upstream points. There is a delay between the upstream and midstream points, but it is difficult to detect at this scale. Panel **(c)** shows the water depth ~~, and panel **(d)** the shear stress, both~~ plotted at the ~~peak~~ time of ~~this~~ the outlet hydrograph peak, as noted by the arrow in panel in **(b)**. Panel **(d)** shows the local maximum shear stress value at each point, over the duration of the model run. Note that the discontinuities in the shear stress figure are a result of the uneven bed topography, and variations in the surface water slope linked to that topography.

Cartoon illustrating the differences between steady-state and nonsteady hydrology and incision at a single point within a watershed. In this schematic, the effective precipitation rate P is the same for both steady and nonsteady cases. During the precipitation event, steady discharge Q_{ss} and incision rate I_{ss} are constant, driven by that effective precipitation rate and drainage area (A), erodibility (K), water surface slope (S) and stream power exponents (m_{sp}, n_{sp}). In the nonsteady case, a wave front begins to propagate and incise, producing time-varying discharge Q_h, calculated using physical parameters such as water depth (h), water surface slope and Manning's roughness coefficient (n). Nonsteady incision rate I_h is calculated using the time-varying discharge, erodibility and water surface slope. At the end of the precipitation event, Q_{ss} and I_{ss} also end, while nonsteady values Q_h and I_h continue until all water has completely exited the system at the outlet.

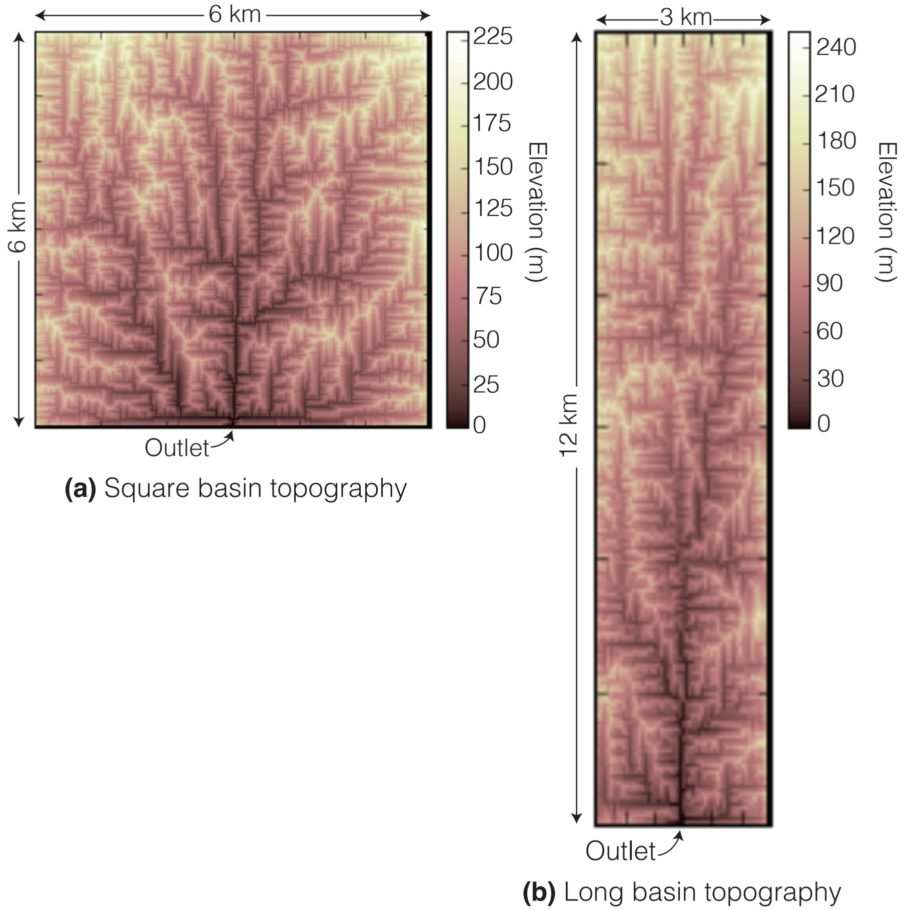

Figure 9. Two test basins evolved using the Landlab FlowRouter and StreamPowerEroder components (not described here, see Hobley et al., 2017), generating a network using D4 flow routing and erosion methods. Each grid was evolved from an initial random topography to steady-statesteady state, where uplift rate is matched by incision rate. Both basins have the same drainage area (36 km^2) at the watershed outlet, but different dimensions: panel **(a)** 200 rows x 200 columns, and panel **(b)** 400 rows x 100 columns. Both have a grid resolution (Δx) of 30 m. Note the perpendicular junctions are due to the D4 flow routing scheme.

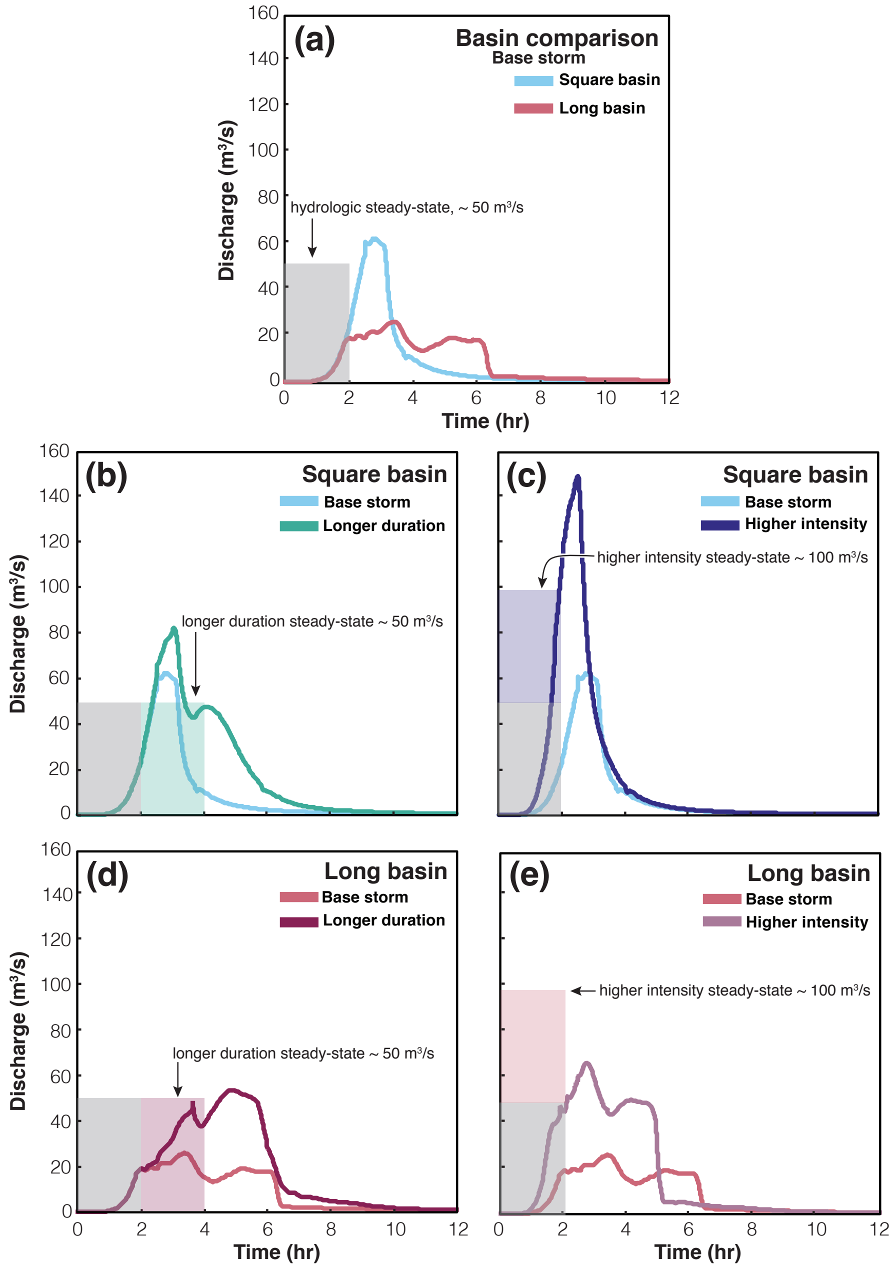

Figure 10. OverlandFlow output for all storms described in Table (**4**). Hydrographs are taken from the active link upstream of the outlet node. Steady-state discharge is shown for each event, with the gray box representing the base storm in all cases. Panel **(a)** shows the base storm for both the square basin and the long basin; panel **(b)** compares outlet hydrographs from the base and longer duration storms in the square basin; panel **(c)** compares outlet hydrographs from the base and higher intensity storms in the square basin; panel **(d)** compares outlet hydrographs from the base and longer duration storms in the long basin; panel **(e)** compares outlet hydrographs from the base and higher intensity storms in the long basin.

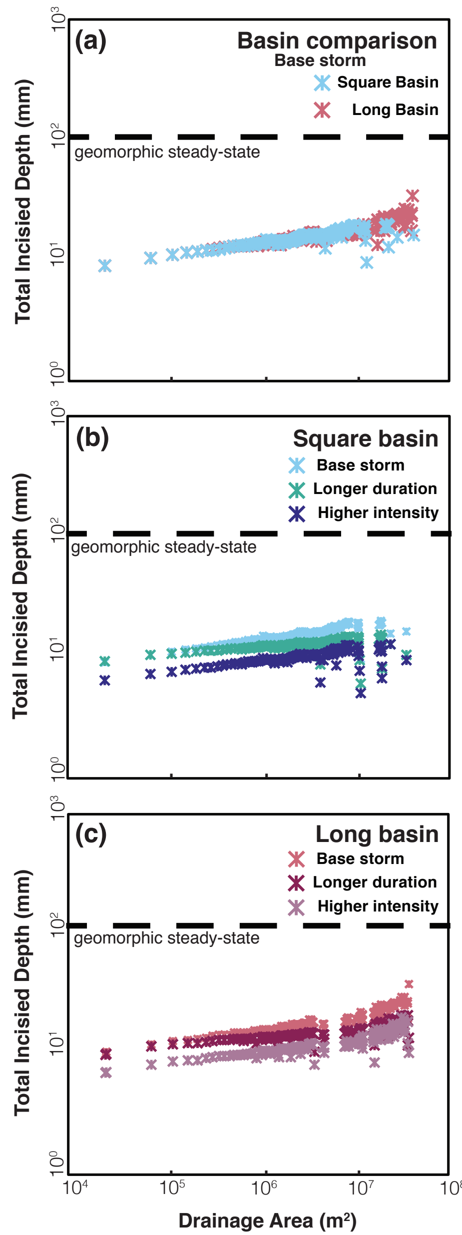

Figure 11. DetachmentLtdErosion output for all storms described in Table (4). Incision depth was taken after 10 years of modeled storms from the OverlandFlow component for all grid locations. The average incision depth was plotted at each drainage area: panel **(a)** shows incision depth versus drainage area for both the square and long basin after 10 years of the base storm; panel **(b)** shows total incision results from the square basin for all three precipitation events after 10 years; and panel **(c)** shows total incision results from the long basin for all three precipitation events after 10 years.

Table 1. List of variables used in the OverlandFlow and DetachmentLtdErosion. For each variable the name, grid element and units are given.

Variable	**Name**	**Grid element**	**Units**
q	water discharge	link	$m^2 s^{-1}$
h_f	local maximum water depth	link	m
S_w	water surface slope	link	–
h	water depth	node	m
Q_h	water discharge from hydrograph method	node	$m^3 s^{-1}$
I	incision rate	node	ms^{-1}
$S_{w_{max}}$	local maximum water surface slope	node	–

Table 2. List of parameters used in the OverlandFlow and DetachmentLtdErosion. For each variable the name and units are given.

Parameter	Name	Default value	Units
Δt	time step	adaptive	s
h_init	initial water depth	0.01	mm
α	stability coefficient	0.7	–
g	gravity	9.81	ms^{-2}
θ	weighting parameter	0.8	–
n	Manning's n, surface roughness coefficient	0.3	$sm^{-1/3}$
K	erodibility coefficient	$1.26 * 10^{-7}$	$m^{1-2m_{sp}}s^{-1}$
m_{sp}	stream power coefficient	0.5	–
n_{sp}	stream power coefficient	1.0	–
β	entrainment threshold	0.0	ms^{-1}
ρ	fluid density	1000.0	$kg\ m^{-3}$

Table 3. Grid characteristics and parameters for analytical solution tests.

Test	**Δx**	**Grid rows**	**Grid Columns**	**n** ($sm^{-1/3}$)	**u** (ms^{-1})	**t** (s)
Resolution sensitivity	5	160	1200	0.03	1.0	3600
	10	80	600	0.03	1.0	3600
	25	32	240	0.03	1.0	3600
	50	16	120	0.03	1.0	3600
Low friction roughness	25	32	240	0.1	0.4	2700 - 9000
High friction roughness	25	32	240	0.01	0.4	2700 - 9000

Table 4. Precipitation parameters for the three storm cases routed across the test basins.

Storm ID	**Intensity** (mm hr^{-1})	**Duration** (hr)
Base Storm	5.0 ~~$mm\ hr^{-1}$~~	2 ~~hr~~
Longer Duration	5.0 ~~$mm\ hr^{-1}$~~	4 ~~hr~~
Higher Intensity	~~10 $mm\ hr^{-1}$~~ 10.0	2 ~~hr~~

Algorithm 1 Sample Landlab overland flow and erosion model

```
from landlab.components import OverlandFlow, DetachmentLtdErosion, SinkFiller    #Import Landlab components and utilities
from landlab.io import read_esri_ascii
(grid, elevations) = read_esri_ascii(asc_file='watershed_DEM.asc', name='topographic__elevation') #Read in DEM and create grid
grid.set_watershed_boundary_condition(elevations, nodata_value = -9999.0)    #Set boundary conditions
effective_rain_rate_ms = 5.0 * (2.78 * 10^-7)    #Convert rainfall from mm hr^-1 to m s^-1
dle = DetachmentLtdErosion(grid)    #Instantiate components and set parameters
of = OverlandFlow(grid, steep_slopes=TRUE, rainfall_intensity = effective_rain_rate_ms)
sf = SinkFiller(grid, routing='D4')
sf.fill_pits()    #Pre-process DEM and fill pits in D4 flow-routing scheme
elapsed_time = 0.0    #Start time in seconds
while elapsed_time < 36000.0 :    #Run for 10 modeled hours
    Δt = calculate_time_step()    #Calculate stable time step
    of.overland_flow(dt = Δt)    #Generate overland flow
# Below, populate fields with water discharge and water surface slope to be shared across components
    grid['node']['surface_water__discharge'] = of.discharge_mapper(of.q, convert_to_volume = True)
    grid['node']['water_surface__slope'] = (of.water_surface_slope[grid.links_at_node] * grid.active_link_dirs_at_node).max(axis=1)
    dle.erode(dt = Δt, discharge_cms = 'surface_water__discharge', slope = 'water_surface__slope')    #Erode the landscape
    elapsed_time += Δt    #Updated elapsed time
```