

## ***Interactive Comment on: Perspective – Synthetic DEMs: A vital underpinning for the quantitative future of landform analysis?***

We thank Jon Pelletier, Ian Evans and an anonymous reviewer for their fair yet rigorous comments on our submitted manuscript; for ease we refer to them by number i.e., [R1], [R2], and [R3] respectively. We have addressed each of the reviewers' comments, as detailed in the attached pdf and summarized below.

Summary of reviewers' comments,

Overall, the reviewers' comments [R1-3] were positive, agreeing with us that synthetic DEMs (i.e., generated landscapes including idealized geometries or the consequences of analytical solutions to governing PDEs) should be encouraged as a tool to enhance the rigor of our analyses of landscapes. They also found our attempt to draw from experience in a wide range of fields useful [R1-3].

In addition, R1 felt that the main message could be clearer; i.e. synthetic DEMs have the potential to add rigor to key parts of the (in)validation of geomorphological theories by comparison to real landscapes. R2 suggested that the typology might be expanded or refined, and that the impression should not be given that tests with synthetics should not replace those against reality. This last point was also made by R3, who requested some additions.

Our response and related changes to the manuscript

We have connected this work to the wider literature on model validation, as suggested by R1, although given the vast size of this literature (as noted by R1) we are limited to touching upon the key points. Fig. 2 has been completely revised, consistent with the wishes of R2, and a paragraph has been added to the start of the introduction.

We have re-ordered the abstract, rephrasing where necessary to reflect this broader context and also to convey the key message of the paper more clearly along the lines suggested by R1. This is followed through into the text, for instance re-ordering the end of section 2.

We have also used the revision to Fig. 2 (now new Fig. 1) to clarify the message of the paper by placing different conceptions of what might be considered a synthetic DEM into context. Furthermore, whilst doing this, we realised that a DEM measured from laboratory experiment could also readily be considered a synthetic DEM; at least, the arguments we put forward needed virtually no modification to encompass this addition.

In making these corrections, and modifying Fig. 2, we hope that it is now clear that we are not advocating analyses with synthetic DEMs as an alternative to measurements of real landscapes; indeed we see synthetic test as a means to more robustly validate concepts through establishing if they reproduce real-world observations.

We have added a Fig. 7 in response to a request by R3.

We have also made changes to account for all the detailed points made by the reviewers.



## **Final Response on: Perspective – Synthetic DEMs: A vital underpinning for the quantitative future of landform analysis?**

### **Detailed responses to reviewers' comments.**

P3L14 = Page 3 Line 14, and refer to the reviewed manuscript.

Reviewer's comments are in grey, with our responses afterwards and with a chevron.

A Word document including tracked changes is also provided.

Fig. 2 = Figure in the reviewed manuscript, unless explicitly stated otherwise.

#### **Reviewer 1: J. Pelletier**

This paper is a very thoughtful perspective piece on the efficacy of synthetic DEMs (e.g. idealized landscapes made from numerical landscape evolution models, analytic solutions to the fundamental PDEs, with and without the noise typical of nature) in geomorphic studies. The authors motivate their study by noting that landscape evolution studies often involve the inference of process from form, but making such inferences is rarely clear cut. Moreover, they note that new models and DEM analyses techniques are often demonstrated on real DEMs. Such validation exercises may not be as effective as using synthetic DEMs that have the advantage of user control on the morphology, degree of stochastic variability, etc. The authors provide a typology of synthetic DEMs that will be a useful guide to future researchers who wish to use them in their work.

> Thank you.

I enjoyed reading the paper and think it makes some excellent points. One particular strength is that it draws from an impressively wide range of geomorphology (all sub- fields are represented) and even other subfields of Earth science (e.g. examples of data processing algorithms used in deep-Earth studies).

> Thank you.

Points for the authors to consider as they revise their work:

I think the key message in this paper can be made more succinctly: the results of any proposed numerical landscape evolution model or DEM-analysis algorithm must return the exact answer for at least one case (similar to the intended application of the model) in which an analytic or exact solution is available. I agree with the basic message of the authors that this should always be done but often is not (including in my own work). One consequence of this point is that some synthetic DEMs (type 2, i.e. those created from landscape evolution models) actually require other synthetic DEMs (type 1, i.e. analytic solutions of the governing equations for simple geometries and forcings) to be established as proper synthetic DEMs. To make this validation- related point stronger, the authors could consider connecting to the large literature on the necessary conditions of model validation (or, more generally, on the kinds of confidence building that should be performed on a model to check whether it meets minimum standards of quality for its intended purpose).

> In order to make the key message more succinctly and clearly, we have re-organised the abstract and expressed it in the sentence: "A second, arguably under-utilised, role is to perform checks on accuracy and robustness that we dub 'synthetic tests'". This is not as specific as suggested by R1, largely because examination of the validation literature (as also suggested by R1) highlights additional facets of the point, which forced us to remain somewhat general.

> As R1 suggests, we have connected this work to the wider literature on model validation. Given the vast size of this literature as noted by R1, we are limited to touching upon the key points. However, we used it to completely revise Fig. 2, and move it to the start of the manuscript to provide a solid context for the manuscript.

> The framework and terminological clarifications in the revised Fig. 2 (now Fig. 1) have been carried through into the manuscript.

The paper raises some interesting issues that I would like to have seen explored more deeply. For example, it is not clear to me how synthetic DEMs can solve the equifinality problem (i.e. similar topography resulting from different processes or forcing histories). At several junctures (including the first bullet point in the conclusions) the paper suggests that the use of synthetic DEMs can mitigate this problem, but precisely how they can was not clear to me.

> R1 is correct that some of the 'other approaches' to predict properties of a landscape (i.e. those which do not create a DEM) might, in some instances, mitigate some aspects of the equifinality problem. Specifically, many processes could (conceptually) give drumlins of the same shape, but if growth is considered statistically only a sub-set of these processes will give the observed size-frequency distribution. The role that synthetic DEMs would have in this would be to add robustness to the observations of size-frequency distributions i.e., the 'observe' on the right hand side of the new Fig. 1. As noted by Hillier et al. [2014] in the Journal of Maps, there is a size-dependent observational bias that we should be cautious of.

> We have not expanded upon this particular aspect here as it is not central to the paper, and is explored more fully in Hillier et al. [In Review] for the case of drumlins; our revisions to that paper will be submitted by the end of the year.

> We believe that the revised manuscript does not explicitly reference 'equifinality'.

The author's criticism of morphological data as typically of a quality that is weakly constrained seems outdated. We can now create bare-earth point clouds/DEMs of unvegetated landscapes on demand with ~1 mm accuracy and comparable resolution using terrestrial laser scanning (Hodge, 2010). This is remarkable by any measure.

> Thank you for noting this. We had not intended to imply that DEMs inaccuracy is a primary concern; it is becoming less so, although in some environments it is still a key problem (e.g. deep oceans). We intended to refer to the quality of metrics derived from DEMs, or at least our knowledge of how good/reliable they are. The sentence in the abstract (P2L7) has now been modified to "Derived morphological properties, including metrics and mapping.....".

As someone who has published on the drumlin problem, I was intrigued by the statement (p. 610) that no process-based model of drumlin formation exists. In Pelletier, Quantitative Modeling of Earth Surface Processes (2008), I proposed a model of drumlin formation by deformation of subglacial till modeled as a deformable porous medium. I think there are process-based models of drumlins that are based on reasonable physics (in the case of my model on the stresses developed during till compaction and dewatering) that match observed relationships between drumlin aspect ratio and average till thickness (this relationship was shown for two US drumlin fields in Pelletier (2008)).

> We thank R1 for highlighting this work, and apologise for not being aware of this model. Pelletier (2008) is now included as a reference, and we have re-phrased the text to remove the assertion that drumlins cannot be obtained from first mathematical principles.

## **Reviewer 2: I. Evans**

The authors make a good case that synthetic landforms are part of the armoury of geomorphological modelling. Synthetic landforms and landscapes are not widely used and this paper should encourage geomorphologists to use them. The advantages and limitations of synthetic DEMs are usefully discussed.

> Thank you.

Readers will find the combination of ideas and examples from different fields useful. The juxtaposition of statistical synthetic DEMs with landscape evolution models is interesting and could be developed in

greater depth, as could the typology: probably further distinctions can be made. For example, a different type of synthetic relief was generated by Griffin: Griffin, MW. 1987. A rapid method for simulating three-dimensional fluvial terrain. *Earth Surface Processes and Landforms* 12(1), 31-38. [Special issue on 'Theoretical Geomorphology']

> To explore the juxtaposition of synthetic DEMs generated by statistical and geometrical means against those synthetic DEMs created by landscape evolution models, Fig. 2 has been revised and used to provide a more detailed conceptual structure that includes their various roles in creating understanding of process from geomorphological form.

> We agree that typology could probably be further refined, and additional distinctions could be made. To this end, we have included DEMs generated by experiment. We have also included reference to Griffin (1987) within section 3.2, noting that distinctions in LEMs exist, but have chosen not to make further distinctions explicit here to achieve a balance between complexity and usability in the typology. We do state that the typology intends to cover the broad approaches (P9L6).

I would assert that models need to be tested against real topography, whether or not synthetic DEMs are used to provide complementary tests. They should not be regarded as alternatives.

> We agree with this assertion, and were not intending to indicate that they should be regarded as alternatives. We see synthetic DEMs and tests as complementary in that they can increase the quality of comparisons between model and real DEMs (i.e. used to improve accuracy, or at least to understand the level of error present when interpreting results). We hope the revised Fig 2 clarifies this.

Some complexities of testing different algorithms for surface metrics are illustrated in –

Minár, J., Jenc̣o, M., Pacina, J., Evans, I. S., Minár, J. Jnr., Krcho, J., Kadlec, M., Burián L., & Benová, A. 2013. Third-order geomorphometric variables (derivatives) – definition, computation and utilization of changes of curvatures. *International J of GIS*. 27 (7), 1381-1402.

<http://dx.doi.org/10.1080/13658816.2013.792113> and-

Minár, Jozef, Minár Jozef Jr & Evans Ian S. 2015 Towards exactness in geomorphometry. In: Jasiewicz J., Zwoliński Zb., Mitasova H., Hengl T. (eds), *Geomorphometry for Geosciences*. Adam Mickiewicz University in Poznań - Institute of Geoecology and Geoinformation, International Society for Geomorphometry, Poznań, *Geomorphometry 2015*. [geomorphometry.org](http://geomorphometry.org) 27-30.

Real and artificial surfaces do tend to give different results!

> Thank you for these references. Minar et al [2013] use what we class a simple or geometrical synthetic DEMs for precisely one of the purposes we highlight; assessing the accuracy of a measure of the properties of a landscape. We have therefore added this reference. As they state, to test the methods "a test mathematical function [placed in a DEM] can be used if it has sufficient characteristics of the land surface". So, whilst real and artificial surfaces will perhaps give different results, the key (as we point out) is to make a synthetic that is sufficiently realistic for the task in hand.

Fig.3 shows that visually the simple model seems an excellent fit. Never the less the profiles in b) show a systematic deviation which is worth commenting. The real profiles have a sharper basal concavity than the model: presumably this betrays the operation of a different process.

> A comment as been added to the end of the first paragraph in Section 3.1.

DETAILS: page/line

Some sentences need to be reworded or simplified for smoother reading.

2/10-11 can this be rephrased to avoid the inverted commas, which may turn off some readers?

> We have removed one of these sets of inverted commas, and placed the other (a new definition) in context in a way that we hope will annoy readers less

3/16 rephrase: it is 'bedforms in flow-sets' – not size of flow-sets. 3/19 'fundamentally random' is an exaggerated interpretation.

> This has been rephrased and moderated to "..... which arguably indicates that substantive elements of the ice-sediment-water system beneath ice sheets contain randomness"

3/20 replace 'similar' – be more specific.

> This has been rephrased to be more specific and read "Quantitative analysis can also provide constraints when applied to linear features ....."

3/22 'are identified'

> 'are' added as requested.

4/19 combine the brackets – don't use 'e.g.' twice.

> Has been altered so that e.g. is not used twice.

6/20 'have uncovered' implies availability of real examples: these should be cited, instead of the hypothetical '50%'.

> An example is now used. The overall detection rates of drumlins during manual mapping is 40-34%, a 60-66% effect [Hillier et al., 2014].

7/4 and 7/11 again, combine the brackets – don't over-use 'e.g.'.

> The brackets have been combined, removing one 'e.g.' in each case.

8/7 is "only possible to test their efficacy. . ." an exaggeration?

> We appreciate that this is a strong statement, but we believe that it is not an exaggeration once it has been modified to 'assess adequately'; clearly an inadequate assessment is always possible (e.g. by astrology). We are defining synthetic DEMs as those containing an a priori correct answer, and the 'observe' part of Fig. 1 requires a DEM for the methods to be applied to. And, this is our definition of a synthetic DEM. We have modified the text to clarify this and to indicate that by adequate we mean in an absolute sense, ruling out mapper inter-comparison as is noted in the bullet points just above this text.

> The only exceptions to this that we can think of are accuracy checks possible when measuring a DEM from an experimental simulator or real landscape, and we are referring to the 'observe' stage (see revised Fig. 2, now Fig. 1) at this point in the manuscript.

9/21 'investigation and'

> 'and' added as requested.

Section 3.1, last para. An early demonstration of the inadequacies of fractal models was – Evans, I. S. & McClean, C. J., 1995 The land surface is not unifractal; variograms, cirque scale and allometry.

Zeitschrift für Geomorphologie, N.F. Supplement-Band 101, 127-147

> Thank you. We have added this reference.

10/16 and 18/26 'Harbor'

> Changed.

11/0 Is anything perfect? Better 'Further improvements are awaited', Or (10/23) 'Several difficulties prevent these models as yet from being ideal solutions.'

> In the first case we have changed to "highly accurate and widely accepted", and to R2's suggestion in the second case.

12/12 To what does 'they' refer? – apparently bedforms, but probably not?

> Originally, 'they' referred to the combination of 'hills' and 'noise'. This statement has now been simplified and clarified. It now focuses on just the noise, which is the particularly difficult part. At least, we do not know of it being attempted in the geomorphological community.

13/2 avoid "to test against synthetic DEMs" – not what you mean?

> Thank you. This is indeed not what we meant. The typographic error in the punctuation has been corrected.

13/26 perhaps 'are not used on the basis that. . .'

> Thank you. This has been changed as suggested.

14/7 not "and perhaps: better, '. . . property and its scale variation is key, it can . . .'

> Thank you. This has been changed.

14/15-19 sentence needs simplification.

> The sentence has been simplified and clarified by separating it into two sentences, with some rewording.

14/23 'later be'

> Thank you. This has been changed.

Fig.1 As the ln scale tends to be opaque to non-mathematicians, I would prefer a log10 scale, or best, actual counts on the y-axis.

> Scale has been changed to log10. An exponential plots linearly on a semi-log plot, so this is used instead of counts to illustrate that the data are visually consistent with an exponential distribution (e.g. instead of a power-law).

Fig.2 I did not find this compound figure useful.

> This figure has now been entirely revised. It is now Fig. 1 in the revised manuscript.

Fig.5 what is the extent of c)? a) is dimensionless but b) would appear to have dimensions.

> All the parts are at the same scale, or in effect so. This information has been added to the caption of the figure. The coefficients used in the modelling were chosen to make this direct comparison possible.

### Reviewer 3: Anonymous

This paper provides an interesting perspective on the use of synthetic DEMs; it introduces the concept of using synthetic DEMs for geomorphology, provides a range of examples from different areas of geomorphology and highlights the role of synthetic DEMs in improving process understanding. I really enjoyed the paper and think that it raised some interesting points and feel that this would make a valuable contribution to ESurf, however some further expansion on some of the points that were introduced in the paper is required.

> Thank you, and please see below.

1. Can you quantify the error difference between observational measurements and synthetic hybrid DEM generation? Each of these have inherent errors within the measurement/computations that are the result of the method used rather than the noise and it would be useful to highlight this in the article.

> We note that these errors exist, but the magnitude of the measurement error depends on the techniques and circumstances of each study, and computational errors (e.g. floating point rounding) should ideally be fixed in the implementation of a model. We have revised Fig. 2 to clarify the procedure in geomorphology intended to link processes to form, which now explicitly includes the step from reality to an observed DEM. This distinguishes between noise and other forms of error. We have also highlighted that variability in both synthetics and observed DEMs can be both random and systematic (P13L4).

> As we note, the use of multiple synthetic DEMs can reduce random errors, and be used to understand the role this might play in observations.

2. What about the importance of initial and boundary conditions? These will influence the generation of the DEM whether it is synthetic or based on observational data, and for process understanding it is important to state the influence that these will potentially have.

> Whether or not initial or boundary conditions have a role in the generation of a synthetic DEM depends upon the type of synthetic DEM (e.g. no role in those of Hillier et al. [2012] or Wessel [1998]). In terms of LEMs, we note the initial and boundary conditions for the simulation we show (Fig. 5b), and a sentence has been added to note that these influence the outcome as well as other model parameters (P8L1).

3. The comparison between the synthetic DEMs and LEMs was touched upon but this could be expanded further with further elucidation of the methods that were used to compare accuracy. Also, although the representation of LEMs is improving, I still do not feel that you can fully test the replicability of synthetic DEMs without drawing on observational measurements from nature; again this was mentioned but more discussion could be centred around this and what impact the simplifications made in LEMs and to some extent synthetic DEMs will affect the resultant DEM and its 'representativeness'.

> As we note, and from our experience, what classes as sufficient representativeness depends almost entirely upon the task in hand and upon the requirements of practitioners in each particular field. We also note the challenge is to "determine a generalised objective framework or workflow to assess the sufficiency of the realism of synthetic DEMs"; this is a challenge that we hope will be taken up, but is beyond the intended scope of this paper.

> We entirely agree that observational measurements from nature are needed, and are strengthened rather than replaced by using synthetic DEMs (see reply to R1 above).

> Although we acknowledge that detailed discussion of the methods and metrics used to compare DEMs is useful, this is not the focus of this paper; we hope to highlight that whatever method is used, testing it with synthetic DEMs can give some better understanding of how well it performs.



4. "Hybrid DEMs" – a figure would be useful showing the DEMs produced and comparison of these with those in nature, so that the reader can visually compare and evaluate the difference between the DEMs produced from real/simple/LEM/hybrid simulations.

> 'Hybrid DEMs' are not a single process or procedure, in fact the opposite of it. Similar goes for the other classes of synthetic DEM. So, no single figure can hope to illustrate and evaluate the differences between them. Indeed, evaluation depends entirely upon the context for which they were designed, which will differ. However, we note that we have illustrated real (Fig. 3a, 5c), simple (Fig. 5a, 4) and LEM-derived DEMs (Fig. 5b), but only a profile to illustrate the process used to create one possible sort of hybrid DEM. We have therefore added a Figure comparing a hybrid DEM to the real landscape it was created from.

# Perspective – Synthetic DEMs: A vital underpinning for the quantitative future of landform analysis?

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## Abstract

Physical processes, including anthropogenic feedbacks, sculpt planetary surfaces (e.g., Earth's). A fundamental tenet of Geomorphology is that the shapes created, when combined with other measurements, can be used to understand those processes. Artificial or synthetic Digital Elevation Models (DEMs) might be vital in progressing further with this endeavour in two ways. First, synthetic DEMs can be built (e.g., by directly using governing equations) to encapsulate the processes, making predictions from theory. A second, arguably under-utilised, role is to perform checks on accuracy and robustness that we dub 'synthetic tests'. Specifically, synthetic DEMs can contain a priori known, idealised morphologies that numerical landscape evolution models, DEM-analysis algorithms, and even manual mapping can be assessed against. Some such tests, for instance examining inaccuracies caused by noise, are moderately commonly employed whilst others are much less so. Derived morphological properties, including metrics and mapping (manual and automated) are required to establish whether or not conceptual models represent reality well, but at present their quality is typically weakly constrained (e.g., by mapper inter-comparison). Relatively rare examples illustrate how synthetic tests can make strong 'absolute' statements about landform detection and quantification; e.g., 84% of valley heads in the real landscape are identified correctly. From our perspective, it is vital to verify such statistics quantifying the properties of landscapes as ultimately this is the link between physics-driven models of processes

33 | and morphological observations that allows quantitative hypotheses to be tested. As  
34 | such the additional rigor possible with this second usage of synthetic DEMs feeds  
35 | directly into a problem central to the validity of much of geomorphology. Thus, this note  
36 | introduces synthetic tests and DEMs, then it outlines a typology of synthetic DEMs  
37 | along with their benefits, challenges and future potential to provide constraints and  
38 | insights. The aim is to discuss how we best proceed with uncertainty-aware landscape  
39 | analysis to examine physical processes.

## 40 1 Introduction

41 Physical processes sculpt planetary surfaces such as the Earth's. A fundamental tenet  
42 of Geomorphology is that the form of the surface created, when combined with other  
43 data or modelling, can be used to understand those processes. This endeavour to  
44 reconcile observation and theory is, essentially, model validation [e.g., Martin and  
45 Church, 2004; Pretty, 2009; 2010] summarized by the question: Has the right model  
46 been constructed? [Balci, 1998]. Fig. 1 illustrates the pathways towards reconciliation  
47 between observations and models, which in geomorphology is conducted through some  
48 properties or metrics diagnostic of the landscape of interest; the pathways lead to this  
49 reckoning from both physical reality and from conceptual models, which may vary in  
50 sophistication (e.g., may even be qualitative). Whilst visual comparisons of landscape  
51 properties are obviously possible, quantitative morphometrics of DEMs ('observe' in Fig.  
52 1) are a stronger approach and these vary according to the types of study being  
53 undertaken.

54 Discrete landforms [cf. Evans, 2012] (e.g., craters, cirques, drumlins, volcanoes) can be  
55 delimited with a closed boundary and then isolated in order to quantify key  
56 characteristics such as height  $H$  or slope of a flank [e.g., Hillier, 2008]. Linear features  
57 (e.g., rivers) can also be measured. Equally, spatially continuous properties of Digital  
58 Elevation Models (DEMs) can be quantified (e.g., roughness, Wetness Index) [Beben  
59 and Kirkby, 1979; Grohmann et al., 2011; Eisank et al. 2014]. Such morphology-derived  
60 observational data, including metrics from mapping that is both manual and automated,  
61 add to the more qualitative assessments that may be drawn directly from  
62 geomorphological maps.

63 Quantifying discrete landforms can give additional insights and provide constraints on  
64 models of physical processes. For example, discrete fluvial bedforms and their  
65 variability are quantified and used to predict extremes for engineering purposes (e.g.,  
66 depth to place a pipeline) [van der Mark et al., 2008]. Impact crater size-frequency  
67 distributions are used to estimate the age of the surface of the Moon and planetary  
68 bodies (e.g., Mars and Mercury) [e.g., Hartmann and Neukum, 2001; Ivanov, 2002].  
69 Similarly, size-frequency distributions of volcanoes have been used to examine how  
70 melt penetrates the tectonic plates [e.g., Wessel, 2001; Hillier and Watts, 2007]. Aeolian  
71 dune formation can be constrained by their sizes [e.g., Duran, 2011; Bo et al., 2011]. In  
72 sub-glacial geomorphology 'flow-sets' of proximal bedforms thought to created by the  
73 same ice motion occur exponentially less often as their size increases (Fig. 2), which

74 | arguably indicates that substantive elements of the ice-sediment-water system beneath  
75 | ice sheets contain randomness [Hillier et al., 2013].

76 | Quantitative analysis can also provide constraints when applied to linear features and  
77 | spatially continuous measures. Channel geometry is measured to investigate the  
78 | influences of tectonic or climatic landscape forcing [e.g., Brummer and Montgomery,  
79 | 2003; Wohl, 2004; Sofia et al., 2015], and channel networks are identified to evaluate  
80 | hydrological responses in floodplains [e.g., Cazorzi et al. 2013]. Continuous measures  
81 | such as curvature can arguably distinguish dominant geomorphic processes (e.g.,  
82 | diffusive vs fluvial) [e.g., Tarolli and Dalla Fontana, 2009; Lashermes et al., 2007], and  
83 | can be designed to detect the presence of anthropogenic features (e.g., agricultural  
84 | terraces) [Sofia, et al., 2014]. They can also be used to estimate the probability of  
85 | landsliding during rainstorms or for (semi-)automated geomorphological mapping [e.g.,  
86 | Tarolli and Tarboton, 2006; Milledge et al., 2009; Eisank et al., 2014]. Thus, such  
87 | quantifications also have value for geomorphic understanding. Importantly, these  
88 | examples illustrate how a robust, reproducible and quantitative approach can be used to  
89 | develop our understanding of process.

90 | Any enhanced use of landform observations, however, relies on us being able to trust  
91 | what we have mapped or quantified. Specifically, the key question is; in terms of  
92 | precision, accuracy and mapping completeness to what extent is it possible to trust the  
93 | metrics derived from morphometric quantification of the landforms or surface recorded  
94 | in the DEMs?

95 | One way around this difficulty is to derive descriptive statistics that are as robust as  
96 | possible to observational shortcomings [e.g., Hillier et al., 2013; Sofia et al, 2013; Tseng  
97 | et al., 2015]. Another solution is to assess the quality of the morphological mapping and  
98 | quantification, perhaps either by an estimate of data completeness or quality [e.g.,  
99 | Hillier & Watts, 2007] or by traditional inter-comparisons between mappers [e.g.,  
100 | Podwysocki et al, 1975; Siegal, 1977; Smith and Clark, 2005] or techniques [e.g.,  
101 | Sithole et al., 2004]. The difficulty with robust statistics is that they will still be distorted if  
102 | shortcomings are substantial [e.g., Hillier and Watts, 2004], and inter-comparisons can  
103 | only ever yield relative levels of success and even complete agreement is inconclusive;  
104 | all techniques, mappers, or techniques calibrated to mappers [e.g., Robb et al., 2015]  
105 | may be systematically missing things (e.g., smaller features [Eisank et al., 2014; Hillier  
106 | et al., 2014]). Furthermore, it is simply not possible to calculate or estimate the  
107 | magnitude of potential systematic biases within these approaches. An alternative is to  
108 | verify each method or result against suitable features or properties known *a priori* within

109 a suitably constructed test DEM. Thus designed landscapes, or ‘synthetic’ DEMs, can  
110 give strong ‘absolute’ answers (e.g., 84% of valley heads in the real landscape are  
111 identified correctly), and may be vital in allowing us to proceed better with uncertainty-  
112 aware landscape analysis to examine physical processes.

113 Synthetic DEMs built by directly using postulated governing equations that encapsulate  
114 processes, or Landscape Evolution Models (LEMs) [e.g., Chase, 1992], are another key  
115 part of examining the form-process link. By altering their constants (e.g., rainfall,  
116 hillslope diffusivity) and mathematical construction they can give insights into the drivers  
117 and impacts of physical processes [e.g., Willgoose et al., 1991; Montgomery and  
118 Dietrich, 1994; Miyamoto and Sasaki, 1997]. LEMs are, however, not yet the whole  
119 solution since to be securely compared to reality equivalent landforms within both DEM  
120 types must still be robustly quantified, sometimes making validation or calibration very  
121 difficult [e.g., Martin and Church, 2004; DeLong et al., 2007]. It is also possible to use  
122 synthetic DEMs to test for inaccuracies in DEMs created by LEMs or by measuring a  
123 landscape (i.e., ‘make’ in Fig. 1); one example of this might be requiring that LEMs  
124 replicate analytic solutions of the governing equations for simple geometries and  
125 forcings. Ultimately, all synthetic DEMs originate in a conceptual view of at least one  
126 aspect of a landscape (e.g., drumlin shape, stream-power based fluvial behaviour).

127 This note introduces synthetic tests and DEMs, then it outlines a typology of synthetic  
128 DEMs along with their benefits, challenges and future potential to provide constraints  
129 and insights. Note that ‘virtual’ and ‘artificial’ are used interchangeably with ‘synthetic’,  
130 as they are in the literature.

131

## 132 **2 Synthetic Tests and the Potential Uses of Synthetic DEMs**

133 In fields such as geophysics it is standard to verify any method against its performance  
134 on some idealised or ‘synthetic’ data. A well-documented example is the classic  
135 ‘synthetic checkerboard’ test [e.g., Dziewonski et al., 1977, Saygin and Kennett, 2010]  
136 used in tomographic imaging of the Earth’s interior. Broadly, there are four requisite  
137 stages for such a test based upon synthetic data [e.g., Nolet et al., 2007].

138

139 1. *Construct a synthetic input* including any features of interest (e.g., the  
140 morphology of a landform).

- 141 2. *Create the synthetic data* that resembles the observed data, for instance adding  
142 suitable noise.
- 143 3. *Invert the synthetic data* using the same numerical approach applied to the  
144 observed data.
- 145 4. *Compare the inverted result with the synthetic input* to see how well the assumed  
146 synthetic input (e.g., landform) is recovered.

147

148 The difficulty always lies in generating a suitable, statistically representative synthetic; in  
149 the case of geomorphology the task is to create an 'appropriate' synthetic landscape or  
150 DEM that is realistic enough in the aspects under investigation.

151 DEMs containing a synthetic component have been employed in 'synthetic tests' to  
152 assess approaches used to estimate the fractal dimension of topography [Malinverno,  
153 1989; Rodriguez-Iturbe and Rinaldo, 1997; Tate, 1998a,b], slope and aspect [Zhou,  
154 2004], land surface parameters (LSPs) [e.g., Wechsler, 2006; Sofia et al, 2013], and the  
155 reliability of DEMs [e.g., Fischer, 1998; Oksanen, 2010]. Additionally, they have been  
156 used to evaluate how well some features (e.g., river networks, terraces) are identified  
157 [Pelletier, 2013; Sofia et al., 2014] and others (e.g., submarine volcanoes and drumlins)  
158 are isolated in 3D (i.e., their volumes explicitly delimited) [Wessel, 1998; Hillier, 2008;  
159 Kim and Wessel, 2008; Hillier & Smith, 2014]. Synthetics have also been used to  
160 assess algorithms quantifying landscape processes such as flow-routing [e.g., Pelletier,  
161 2010] and to give a first insight into how effective the manual mapping of glacial  
162 bedforms is [Hillier et al., 2014]. Often, when including randomness (e.g., in locations or  
163 noise) in a *Monte Carlo* approach multiple realisations of a landscape (e.g.,  $n = 10$  or  
164 1,000) are used to understand uncertainty and variability and more tightly constrain  
165 results [e.g., Heuvenlink, 1998; Raaflaub and Collins, 2006; Wechsler, 2006]. The large  
166 | (e.g., [60-66% in Hillier et al. \[2014\]](#)) and systematic trends and biases that studies so far  
167 have uncovered indicates that the uses of synthetic tests in geomorphology should be,  
168 arguably, similar in extent and function to the current use of inferential statistics; namely  
169 they are a demonstration that the observation claimed actually exists or method actually  
170 works. Some potential applications of synthetic tests in geomorphology can be  
171 categorised as:

172

- 173 • Assessing the impact of 'noise' [e.g., Sofia et al., 2013; Zhou and Liu, 2002,  
174 2008] that could be instrumental, anthropogenic (e.g., houses) or natural (e.g.,

175 | vegetation). This applies to making DEMs from measurement, and making  
176 | quantitative observations from any DEM.

- 177 | • When observing, verifying that a geomorphic signature is actually characteristic  
178 | of a particular landform type of interest, rather than other morphologies in a study  
179 | area [e.g., Conway et al., 2011; Sofia et al., 2014].
- 180 | • Quantifying extraction of features using metrics such as completeness, reliability  
181 | [e.g., Hillier et al., 2014; Eisank et al., 2014]; in this the key advantage is that  
182 | synthetics give 'absolute' measures of accuracy simply not possible with  
183 | traditional mapper inter-comparisons (e.g., 34-40% of drumlins can be detected).
- 184 | • Assessing filtering or other techniques used to manipulate a DEM [e.g., Hillier &  
185 | Smith, 2014], whose choice would otherwise be subjective.
- 186 | • Evaluating the sensitivity of algorithms quantifying geomorphic processes to  
187 | modelling assumptions, such as DEM resolution [e.g., Pelletier, 2010].
- 188 | • Determining whether or not LEMs have been correctly constructed (i.e. 'make' in  
189 | Fig. 1).

190 | Ultimately, the geomorphological intention is to use synthetic DEMs to examine more  
191 | clearly the expression of physical processes. Rigor added to geomorphological  
192 | observations through testing with synthetic DEMs will, we believe, ultimately link  
193 | physics-driven models of processes to morphological observations, allowing quantitative  
194 | hypotheses to be formulated and tested [e.g., see McCoy, 2015]. This is illustrated in  
195 | Fig. 1, the crux of which is that it is necessary to quantify landscape properties to  
196 | rigorously reconcile DEMs, with some main elements of this described in more detail  
197 | below.

198 | If arguably realistic forms can be generated directly by a physics-based model [e.g.,  
199 | Dunlop et al., 2008; Refince et al., 2012; Brown, 2015] creating a synthetic DEM, these  
200 | may in principle be linked directly to reality if suitably equivalent field sites can be found,  
201 | measured, and recorded in a DEM. The effects of various constants (e.g., rainfall),  
202 | conditions and processes in the physical models on observables can be viewed and  
203 | compared to reality by the simple expedient of turning them off or amplifying them, of  
204 | course allowing carefully for appropriate initial and boundary conditions. Comparisons  
205 | have been qualitative [e.g., Kaufman, 2001], but can provide more powerful insights if  
206 | they apply consistent mapping or quantification procedures [e.g., Willgoose et al., 1994].  
207 | Thus, creating a form-process link will still depend critically upon understanding any  
208 | errors or biases in landform morphometrics (e.g., in size-frequency distributions,  
209 | dominant wavelength) for both the measured and generated landscapes (i.e., 'observe'



210 | in Fig. 1). The appropriate metrics are better understood for some landforms than for  
211 | others, and it is only possible to adequately assess their efficacy (i.e. in an absolute  
212 | sense) with tests involving a priori information and a DEM to apply the morphometric  
213 | extraction method to, or by our definition using a synthetic DEM. If laboratory  
214 | experiment replaces LEM-derived synthetic DEMs in the paragraph above, the same  
215 | logic applies.

216 | For a landform that it is not yet possible to create numerically from first mathematical  
217 | principles, other routes exist. The challenge is to securely relate the driving process  
218 | (e.g., tectonic uplift rate) to a measure of morphology (i.e., 'conceptual model' to  
219 | 'landscape properties' on Fig. 1), perhaps using its variability within geographical areas.  
220 | For example, drumlin sizes observed for a number of flow-sets might be compared to  
221 | characteristics of flow within a modelled ice sheet (e.g., flow velocity) representative of  
222 | the area of the flow-set. Statistical models can be formulated that link size-frequency  
223 | observations to parameters in numerical ice-flow models [Hillier et al., in review], but  
224 | even potential empirical rules about timing (e.g., immediately before de-glaciation) and  
225 | the relationships to ice flow (e.g., size directly proportional to velocity) could be tested.  
226 | Robustly determined observational metrics would be needed for such an inversion; i.e.,  
227 | synthetic tests are needed. Realistic models are likely to contain stochastic elements  
228 | [e.g., Tucker et al, 2001], thus a statistical understanding may help to identify more  
229 | effectively appropriate parameterizations for size observations (e.g., Weibull) than  
230 | testing a variety of established distributions [e.g., van der Mark, 2008]. Observational  
231 | robustness is desirable in this case, but also for approaches that make predictions  
232 | about landscape properties directly from conceptual models, for instance dominant  
233 | wavelengths [e.g., Anderson, 1953; Venditti, 2013].

234 | A final use of synthetic DEMs is examining 'what if' engineering scenarios as they affect  
235 | behaviours such as hydrological processes [e.g., Tarolli et al., 2015]. This may be  
236 | somewhat tangential, but imposing a proposed artificial geometry onto a measured  
237 | DEM as a way of testing an artificial geometry to be created on the part of the Earth's  
238 | surface is clearly a legitimate pursuit.

239 |

### 240 | **3 Synthetic DEM Typology**

241 | Synthetic DEMs are only useful if they can be constructed, and their construction must  
242 | be from or clearly identify 'components' (e.g., a landforms layer). In contrast to viewing a  
243 | landscape as plan-view regions, height in DEMs can be described at any location (x, y)

244 as the sum of  $n$  'components' (Eq. 1) [e.g., Wren, 1973; Wessel, 1998; Hillier and Smith,  
245 2008], namely  $H_{\text{DEM}} = H_1 + H_2 + \dots + H_n$ . Conceptually, these components lie on top of  
246 each other, like geological strata, and extend across the entire DEM although they may  
247 have zero thickness for few or many parts of it.

248 For landform analysis the first component would typically be 'noise' (e.g., DEM error, or  
249 surface 'clutter' such as trees), the small-scale height variations not genetically related  
250 to the landform. A second component would be the landforms themselves, perhaps  
251 overlying a third component of larger-scale trends (e.g., 10 km wide smoothly  
252 undulating hills). However, in the limit, only one component is actually required, and  
253 how the components are constructed will vary depending upon the purpose of the  
254 synthetic DEM. Furthermore, the synthetic DEM might mix idealised, created  
255 components with real ones. Typically randomness is involved in the creation of  
256 statistical synthetics, and multiple realisations of landscapes may be created. The broad  
257 approaches to constructing synthetic DEMs are outlined in the typology below.

### 258 **3.1 Simple and Statistical**

259 Perhaps the simplest synthetic DEMs are those constructed by using basic geometries  
260 as building blocks such as cones, Gaussian functions, and planes or other surfaces  
261 defined by simple equations [e.g., Hodgson, 1995; Wessel, 1997; Jones, 1998; Kim  
262 and Wessel, 1998; Hillier, 2008; Pelletier, 2010; Qin et al., 2012]; admittedly, some  
263 functions may be less simple [e.g., Pelletier, 2013; [Minár et al., 2013](#)]. Typically,  
264 generalized shapes (e.g., 2D Gaussian, rotated parabola) are formulated based upon  
265 visual or statistical fitting of the functions to measured morphologies [e.g., Conway et  
266 al., 2011; Hillier and Smith, 2012; Pelletier, 2013] (Fig. 3); [fits may not be perfect \(Fig.  
267 3b\), highlighting that all synthetic DEMs are simplifications of reality.](#)

268 These synthetics do not contain the complexity in the observed landscape, or  
269 necessarily have realistic statistical properties, but they have the advantages of being  
270 simple to construct and understand, and noise can be entirely omitted or modified with  
271 certainty in order to investigate data errors. They contain the key morphologies under  
272 investigation [and](#) are perfectly sufficient for some tests; e.g., are approximately conical  
273 submarine volcanoes of variable size effectively isolated even when upon a slope? (Fig.  
274 4). Statistically generated 'noise' can be added to simple synthetic DEMs to assess the  
275 degradation caused [e.g., Zhou, 2004; Jordan and Watts, 2005], but for results to be  
276 meaningful its statistical distribution (e.g., Gaussian, uniform), length-scale of  
277 correlation, and any non-stationarity must be correct [e.g., Fischer, 1998, Sofia et al.,  
278 2013].

279 Whole landscapes can be generated statistically using fractals [e.g. Mandelbrot, 1983]  
280 or multi-fractals (Fig. 5a) [e.g., Gilbert, 1989; Schertzer and Lovejoy, 1989; Weissen,  
281 1994; Cheng, 1996], and these can be useful if the construction matches closely the  
282 element of reality being considered (e.g., uncorrelated, fractal in Swain and Kirby  
283 [2003]). Even multi-fractal landscapes, however, may not be an adequate  
284 representation without considering properties such as anisotropy [e.g., [Evans and](#)  
285 [McClellan, 1995](#); Gagon, 2006] and characteristic scales [e.g., Perron, 2008] if they are  
286 important in a particular circumstance. A limitation of these purely statistically  
287 generated, or statistically altered, DEMs for landform analysis is that they do not  
288 explicitly contain spatially distinct, isolated features (i.e., landforms are not labelled as  
289 such during generation).

### 290 **3.2 Landscape Evolution Models**

291 DEMs resembling real landscapes can also be created by the application of  
292 mathematical characterisations of physical processes in numerical models typically  
293 known as 'Landscape Evolution Models' (LEMs) (Fig. 5b) [e.g., Chase, 1992; Braun and  
294 [Sambridge, 1997](#)]; [implementation approaches can vary \[see Griffin, 1987\]](#). These now  
295 incorporate numerous processes [e.g., Tucker, 2010; Refice et al., 2012]; for example,  
296 bedrock landslides [e.g., Densmore, 1998], flexure of the lithosphere [e.g. Lane et al.,  
297 2008], and erosion by ice flow within valleys [e.g. Harbor, 1992; Brocklehurst and  
298 Wipple, 2004; Amundson and Iverson, 2006; Tomkin, 2009], including when this is  
299 thermo-mechanically coupled to ice sheets [e.g. Jamieson et al., 2008]. Models of the  
300 evolution of single classes of feature (e.g., bedforms) and simpler 2D configurations  
301 (i.e., x-z profiles) fall within this class of model [cf. Dunlop et al., 2008; Zhang et al.,  
302 2010; Brown et al., 2014]. Simple geometries or measured landscapes may be used as  
303 an input [e.g., DeLong et al., 2007; Refice et al., 2012; Baartman et al., 2015; Hancock  
304 et al., 2015].

305 [Several difficulties prevent these models from, as yet, being ideal solutions.](#) [In terms of](#)  
306 [testing observational methods,](#) the first difficulty is that [the method of generating](#) some  
307 landforms such as drumlins from first principles [is often contested](#) [cf., Hindmarsh,  
308 1998; Schoof, 2007; [Pelletier, 2008](#)], and it is not computationally practical to include  
309 certain processes, such as impact crater formation in the MARSSIM model [Howard,  
310 2007]. [The simulation of rivers illustrates an area where there is progress, but also](#)  
311 [much to do](#) [cf. Coulthard et al., 2013; Brown et al., 2014]. In general, a [highly accurate](#)  
312 [and widely accepted](#) unified model is still some way off. The second difficulty is that  
313 these models do not currently associate processes with a type of landform. For

314 instance, a bedrock failure process is a bedrock failure process, not a bedrock failure  
315 process explicitly making a V-shaped valley. Equally, sediment is not tagged as making  
316 a floodplain. So, the number and location of defined features are not known *a priori*.  
317 This can be seen as a strength of the models, but means that creating a secure link  
318 from process to landforms as observed in reality requires a step in which consistent  
319 mapping or quantification procedures are applied to both measured and simulated  
320 DEMs. This is not easy [e.g., DeLong, 2007]. The lack of *a priori* features may also be  
321 the reason that, although LEMs have great potential to create DEMs for synthetic tests  
322 of landform mapping or extraction methodologies, we are not aware of this being done.  
323 Like simple or statistical synthetic DEMs, synthetics created by a LEM have the  
324 advantage of being free from errors associated with DEM measurement (e.g.,  
325 instrumental, processing).

### 326 **3.3 Laboratory derived**

327 If LEM-derived DEMs can be considered as synthetic DEMs, then laboratory-derived  
328 ones [e.g., Hancock and Willgoose, 2001; Lauge et al. 2003; Graveleau and  
329 Dominguez, 2008; Sweeny et al. 2015] could also be considered so. Such experiments  
330 can control variables such as rainfall and uplift that are impossible to precisely control in  
331 nature [e.g. Sweeny et al 2015], but limitations in realism exist particularly in scaling  
332 [see Paola et al., 2009].

### 333 **3.4 Complex geometrical**

334 A possible class of synthetic DEM is one that uses simple or statistical building blocks,  
335 but constructed in a more complex fashion. For instance, multiple idealised shapes can  
336 be given additional observed attributes (e.g., spatial clustering, size-frequency realism)  
337 [e.g., Howard, 2007; Hillier and Smith, 2012], but such DEMs have so far contained  
338 other elements of realism as well, perhaps making them better described as hybrids.

### 339 **3.5 Hybrid**

340 A 'hybrid' class of synthetic DEM contains, for reasons of practicality, elements of the  
341 other classes. Typically, a morphology whose key properties cannot currently be readily  
342 simulated is either retained (e.g., most or all of a measured DEM), or an idealised but  
343 observationally constrained component is added (e.g., terraces [Sofia et al. 2014]), or  
344 both. The spectrum of what is possible is illustrated by the, relatively rare, studies using  
345 hybrid synthetic DEMs in geomorphology.

346 A first example of a hybrid synthetic DEM is impact crater formation in the MARSSIM  
347 model [Howard, 2007]. This evolution model does not dynamically model crater

348 formation. Instead, randomly located craters are assigned shapes from a catalogue of  
349 measurements of individual fresh craters on Mars and given sizes from a power-law  
350 distribution. This introduces certain assumptions, such as the fresh craters being  
351 representative, but avoids complexity. A second example deals with the quantification of  
352 glacial bedforms, illustrated with drumlins [Hillier and Smith, 2012; Hillier and Smith,  
353 2014; Hillier et al, 2014]. It is the association of the bedforms with underlying trends  
354 (i.e., 'hills') and complex and spatially structured 'noise' (e.g., trees, roads, houses) that  
355 makes the quantification difficult; in particular, this noise is problematic, and  
356 geomorphological analyses have yet to attempt simulating it. The approach taken was  
357 therefore to circumvent this issue entirely by leaving the hills and noise as they were,  
358 and moving the drumlins such that they were randomly positioned with respect to these  
359 problems for identification (Fig. 6). Orientations and spatial density distribution (i.e.,  
360 number per km<sup>2</sup>) were preserved, as were the geometries (i.e., height-width-length  
361 triplets) of the 173 drumlins shuffled around. In these synthetics (Fig. 7), the number  
362 and location of defined features are known *a priori* such that sizes and locations of  
363 mapped discrete landforms can be compared to synthetic ones directly. Similarly, but by  
364 assuming the highest-quality measured LiDAR DEMs were perfect, even if this is  
365 debatable, it is possible to circumvent the need to generate statistically realistic  
366 landscapes when investigating DEM errors [Raaflaub and Collins, 2006; Sofia et al.,  
367 2013]. Anthropogenic elements (e.g., open-cast mines, terraces) visually determined to  
368 be reasonable can also be added [e.g., Baartman et al., 2015], for instance to a 2D  
369 multi-fractal statistical landscape [Sofia et al., 2104; Chen et al. 2015].

370

#### 371 **4 Discussion**

372 By providing an *a priori* known answer to test against, synthetic DEMs or DEMs  
373 containing a synthetic component have some clear and powerful advantages in  
374 geomorphological analyses. They can be used to test errors, systematic or random  
375 biases, and unpick potential sources of misinterpretation. Furthermore, they give  
376 *absolute* answers (e.g., 47% of all actual drumlins  $H > 3$  m are mapped) to questions  
377 about accuracy that are simply not obtainable by other means, and are often considered  
378 'objective'. Through this they provide a route to answering key questions about  
379 geomorphic processes (e.g., Fig. 1). There are, however, complexities surrounding  
380 these statements, which are less commonly recognised. There are issues of objectivity,  
381 realism, circularity and the cost in time and effort of constructing synthetics.

382 Whilst the conclusions reached through the use of synthetics may be simplistically  
383 thought of as objective, it is more accurate to say that they are quantitative,  
384 reproducible, and are likely to be significantly less subjective. Without perfect, all-  
385 purpose synthetics an element of subjectivity will remain in the choices made when  
386 designing the test DEM. Hillier and Smith [2012] illustrate some choices and a logical  
387 justification for them. Manually selecting data to test against [e.g., Sithole, 2004; Hillier  
388 & Watts, 2004] is faster in some circumstances, if more subjective. Reproducibility  
389 makes testing using synthetic DEMs superior to subjective visual verification, even if  
390 synthetic tests later indicate the visual estimate was a reasonable solution [Hillier and  
391 Smith, 2012, 2014]. Pre-existing synthetic DEMs, however, are entirely objective means  
392 for inter-comparison for future studies [e.g., Eisank et al., 2014].

393 A thorny question regarding synthetics is: how realistic is realistic enough? At one limit,  
394 it is notable that even extreme simplifications such as conical volcanoes can give  
395 significant and useful first-order insights [e.g., Kim and Wessel, 2008; Tarolli et al,  
396 | 2015]. At the other limit, synthetic DEMs are not used on the basis that their applicability  
397 to real datasets is questioned [e.g., Robb et al., 2015]. Lacking a perfect set of  
398 properties, however, should not be taken to invalidate tests using a synthetic DEM; in  
399 statistics for instance, Student's t-test underpinned by its idealized Gaussian distribution  
400 is widely used although observations are rarely perfectly Normal. A challenge then is to  
401 determine a generalised objective framework or workflow to assess the sufficiency of  
402 the realism of synthetic DEMs, but in its absence what can be done? Deficiencies can  
403 be visually identified. For instance, if spatial resolution is raised as an issue, it can either  
404 be matched to the observed data, or varied for a sensitivity test. If a particular statistical  
405 | property and its variation with scale is key, it can be measured to ensure it is realistic in  
406 the synthetic. So, if a clearly stated set of properties argued to be most relevant to any  
407 given research task are faithfully reproduced in synthetics, we believe they will provide  
408 useful insights. Ultimately, however, practitioners within a peer-group must decide what  
409 is convincing, performing additional tests if necessary. For example, Hillier and Smith  
410 [2012] did not locally align neighbouring drumlins with each other, but participants the  
411 GMapping workshop [Hillier et al., 2014] felt that this was critical. Modified DEMs with  
412 this property included were therefore provided, although in the end this proved to be a  
413 minor effect. Similarly, what must be captured well in a synthetic DEM may critically  
414 | vary between studies. This is exemplified by the impact of life (e.g., buildings,  
415 earthworks, trees, eco-geomorphic work by worms), which may either be inconvenient



416 'noise' [e.g., Hillier & Smith, 2012] or the morphology of interest [e.g., Dietrich and  
417 Perron, 2006].

418 A more subtle potential issue is circularity. It is important to avoid basing aspects of a  
419 synthetic DEM on an assumption, and then using it to support the assumption. This is  
420 easily avoided in simple synthetic DEMs but a synthetic DEM based on a landscape  
421 evolution model, for instance, should not later be justified because a search algorithm  
422 trained on it finds only similar features in a real landscape; the algorithm might just be  
423 missing things in the real landscape that differ from what it has been trained to detect. A  
424 similar issue was faced by Hillier and Smith [2012], but demonstrably avoided as the  
425 filter later found to be optimal was not the one initially assumed [Hillier and Smith,  
426 2014].

427 So, subjectivity is reduced, even synthetic tests using basic DEMs can give some  
428 insight, and circularity can be avoided. On balance we argue that, if designed  
429 appropriately and used with appropriate care, tests using synthetic DEMs are worth the  
430 cost in time as they can be used to access results and insights of real significance and  
431 power. Exactly the same can be said for the application of statistical techniques, and so  
432 it seems reasonable to advocate the use of synthetic tests with similar strength.

433 By making observations more robust synthetic tests using synthetic DEMs containing a  
434 *priori* known landforms have the potential to strengthen the insights that can be gained  
435 through synthetic DEMs generated using physics-based numerical models, i.e.  
436 Landscape evolution models. LEMs can provide useful insights, but they are not the  
437 entire solution; firstly, they cannot model all processes yet, and secondly they are  
438 insufficient without synthetic tests to secure the observational part of the linkage  
439 between measured and generated DEMs. It is also worth noting that landscape  
440 evolution models are not the only route to creating a form-process link since the other  
441 routes described (e.g., statistical) also provide a quantitative means of establishing a  
442 form-process link even without a LEM. Thus, there are a number of valid types and  
443 specific uses of synthetic DEMs, but in combination we believe that they form a vital  
444 underpinning for the quantitative future of landform analysis [e.g., see McCoy, 2015].

445

## 446 **5 Conclusions**

447 From this discussion on the uses of synthetic digital landscapes (i.e., DEMs), or  
448 synthetic elements within them, the following overarching points can be drawn:

- 449 • Synthetic DEMs can help to link physics-based models of processes to  
450 morphological observations, allowing quantitative hypotheses to be formulated  
451 and tested; importantly, this is not only through the use of landscape evolution  
452 models.
- 453 • By establishing ‘absolute’ answers tests using synthetic DEMs containing *a priori*  
454 known landforms are a powerful tool with which to test and add rigor to  
455 geomorphological observations, and arguably should become as standard as  
456 statistical tests in geomorphology or synthetic test data in other arenas (e.g.,  
457 Geophysics).
- 458 • A ‘perfect’ synthetic DEM faithfully representing all aspects of an environment is  
459 likely impractical or impossible to create at present, but is not necessary.
- 460 • Synthetic DEMs for tests may be easy and simple to construct, yet still provide  
461 valuable insights.
- 462 • Synthetic tests using DEM’s should be tailored to each research question, and  
463 their appropriateness to the key aspects of each inquiry (e.g., resolution, biases,  
464 and sensitivities) set out clearly and logically.

465

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473 **References**

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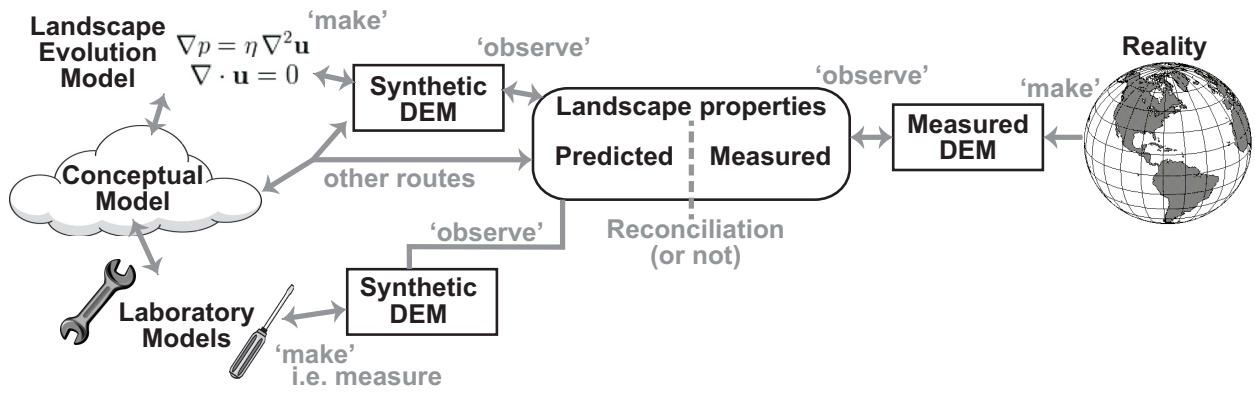
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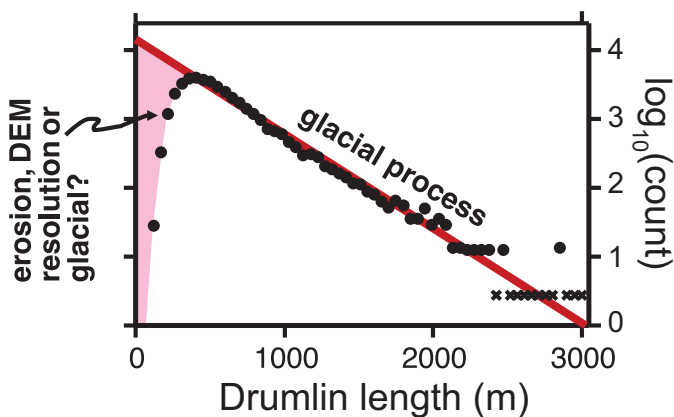




858

859 **Fig 1:** Illustration of the pathways and stages in reconciling geomorphological models  
 860 with reality in order to understand the physical processes that sculpt planetary surfaces.  
 861 Stages are in black, and tasks undertaken to move between them are in grey, with  
 862 double-headed arrows indicating possible feedbacks. Synthetic DEMs may be created  
 863 through various routes, and may be employed to add rigor to both the making of DEMs  
 864 and the observing of them to derive landscape properties.

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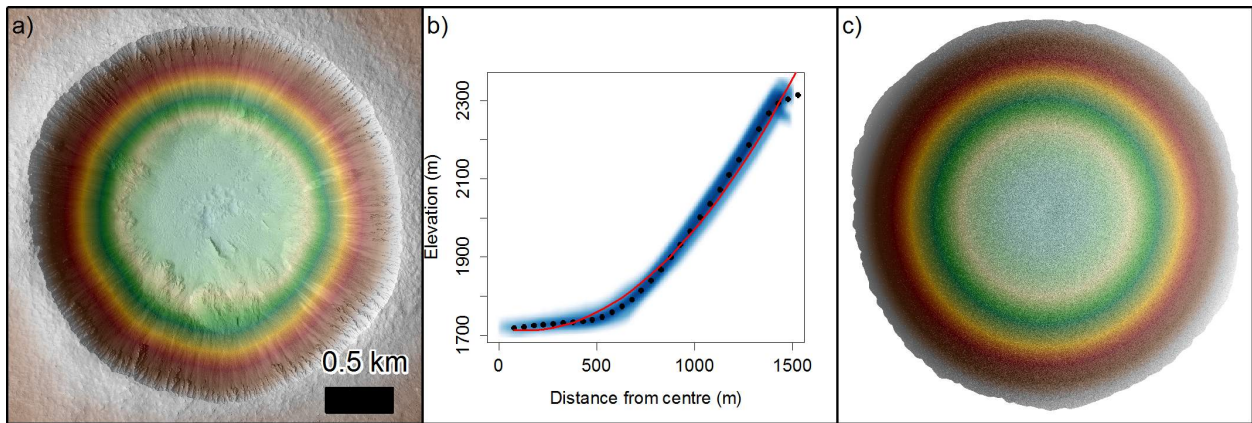
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867 **Fig. 2:** Semi-logarithmic frequency plot of the lengths,  $L$ , of UK drumlins adapted from  
 868 Hillier et al. [2013]. Black dots are data digitised from Fig. 8 of Clark et al. [2009], with a  
 869 bin width of  $\sim 50$  m. Red line is the exponential trend. Crosses indicate zero counts,  
 870 placed at a nominal value of 1. Aspects of the curve are speculatively associated with  
 871 processes, glacial or related to erosion and DEM construction.

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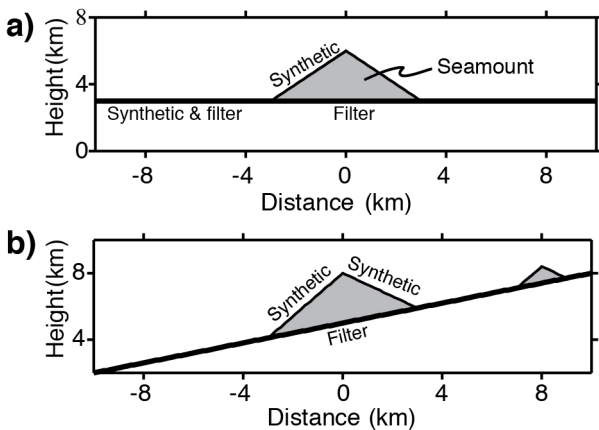
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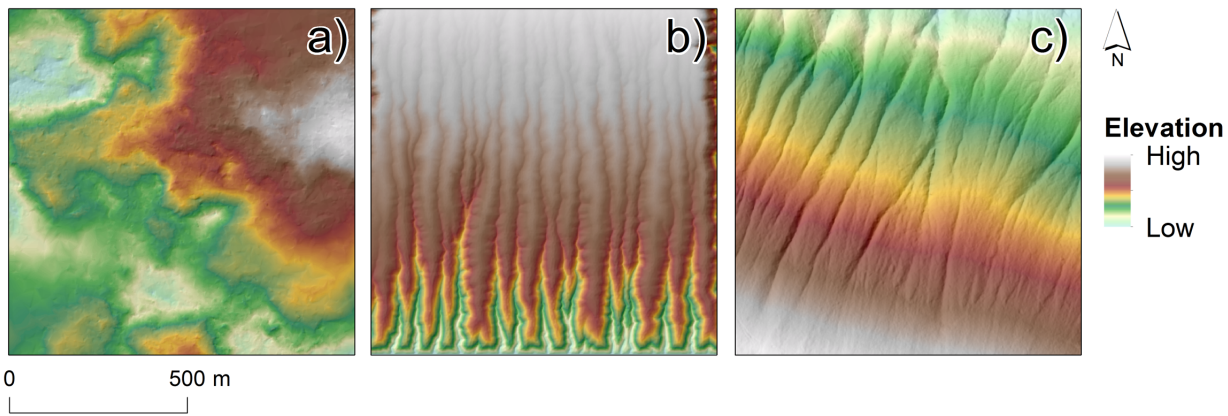
876 **Fig. 3:** a) HiRISE image of Zumba crater on Mars coloured according to elevation;  
 877 HiRISE image DT2EA\_002118\_1510\_003608\_1510\_A01 and DEM  
 878 DTEEC\_002118\_1510\_003608\_1510\_A01, credit NASA/JPL/UofA. b) Radial elevation  
 879 profile; blue shading illustrates the data distribution, black dots are averages within 50 m  
 880 distance bins, and the red line is a parabolic fit to those points. c) A synthetic crater  
 881 created by rotating the parabolic equation, overlain by uncorrelated Gaussian noise and  
 882 displayed as in a).

883



884

885 **Fig. 4:** a) A simple 2D (i.e., distance-height profile) synthetic seamount (grey shading)  
 886 [Hillier, 2008], which following Kim & Wessel [2008] is conical with a radius of 3 km and  
 887 summit height of 3 km above the surrounding seafloor. The thin black line is the  
 888 synthetic topography, and the thick black line the filter's output b) A more demanding  
 889 test of two, variably sized seamounts upon a sloping surface.

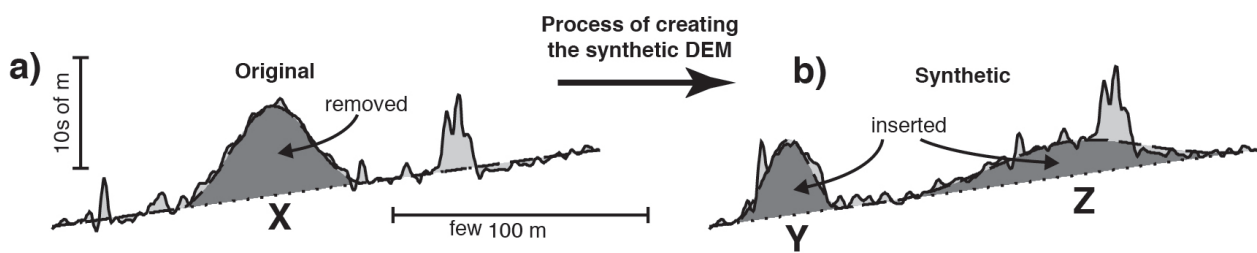


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891 **Fig 5.** Comparison of simulated DEMs in a) and b) with LiDAR measurement of a real  
 892 | landscape in the South of Italy in c). a) Fractional Brownian motion [Mandelbrot, 1983];  
 893 | initial roughness of the surface = 0.2, initial elevation of the surface = 0.0, and change of  
 894 | roughness over change of terrain = 0.005. Output is dimensionless, but is effectively  
 895 | given the same scale and resolution as c) by assigning each pixel a 2x2 m size. b) A  
 896 | landscape model [Refice et al. 2012] that evolves through time a southward-dipping  
 897 | initial topography containing small-scale randomness, with all 4 boundaries closed  
 898 | except lower right corner. Simulated time is ~30 kyr and the run parameters are:  
 899 | tectonic uplift  $u_f = 1$  mm/yr; diffusivity constant  $k_d = 0.2$  m<sup>2</sup>/yr; with channelling  
 900 | parameters of  $K_c = 10^{-4}$  m<sup>(1-2m)</sup>/yr,  $m = 0.5$ , and  $n = 1$ . The spatial dimensions of b) are  
 901 | as in c). Centroid in c) is 14°37'59.46"E, 40°43'25.80"N.

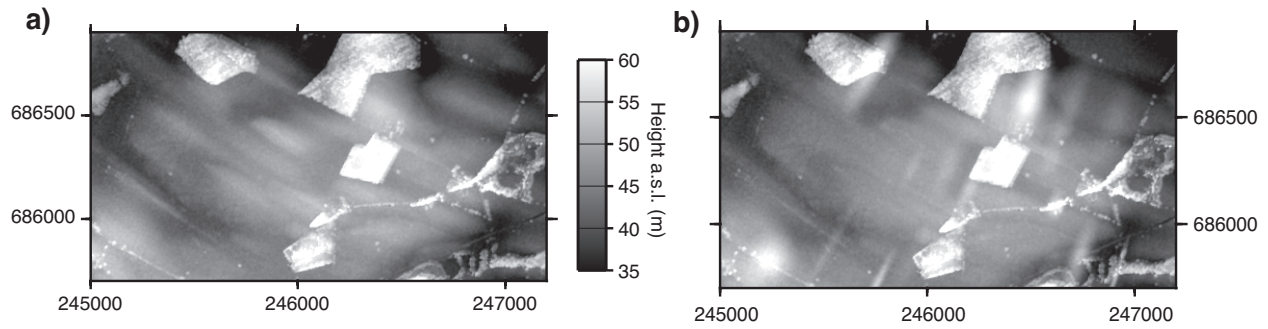
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905 **Fig. 6:** Idealised distance-height profiles to illustrate the process used by Hillier and  
 906 | Smith [2012] to create synthetic DEMs. There are three 'components'. Drumlins, that  
 907 | are shaded dark grey, rise above a regional trend indicated by a dotted line. These are  
 908 | overprinted by 'clutter' or 'noise' shown in light grey. a) In the process the upper and  
 909 | lower surfaces of the drumlin (X) are estimated to define it, and its height is subtracted  
 910 | from the measured DEM. b) Two Gaussian shaped drumlins (Y and Z) are then inserted  
 911 | by adding their height to create the synthetic DEM.



912

913 **Fig. 7:** Illustration of a real DEM in a) and a 'hybrid' synthetic generated from it. Method  
 914 used is as in Fig. 6 [Hillier and Smith, 2012], adapted to locally align drumlins with each  
 915 other [Hillier et al., 2014]. Map coordinates are of the British National Grid (5 m grid).  
 916 Synthetic drumlins were orientated at 90 degrees to the original to avoid any possible  
 917 confusion with any incompletely removed original ice flow fabric during the mapping  
 918 exercise.

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