Editor

Dear Authors,

On previous reviewer and one new reviewer have now considered your revised manuscript. Whilst the new reviewer has a generally favourable view of the manuscript, the original reviewer has more substantial concerns.

I have therefore decided to reconsider the manuscript following major revisions. In addition to responding to the useful comments and suggestions made, I would be grateful if you could carefully consider the claim that the products presented are truly "landform maps", which both reviewers from this round call into question.

Best wishes,

James Thornton

Response:

Thank you very much for your review and support. In response to your and reviewers' comments, we have carefully addressed each point and would like to provide further clarification on the issue you raised regarding whether our results can be considered a landform map.

The primary goal of this study is to characterize the morphological characteristics of the land surface, particularly the vertical variation and relief intensity across different landforms, which are a key component of landform classification. However, we fully acknowledge that in a stricter geomorphological sense, the term "landform" often refers to specific and named units such as valleys or plateaus, as highlighted by Reviewer #1. After carefully consideration and reviewing of related literatures, **we recognize that our understanding of the terminology was imprecise. In light of the comments and guidance from relevant literature [1,2], we have revised the terminology throughout the manuscript, referring to our classification results as relief classes instead of landforms.** The concept of relief classes emphasizes a morphological representation of the terrain, focusing on the vertical variation and intensity of surface undulation rather than specific indices. These relief features play essential roles in regulating energy flow and material transport across the Earth's surface and have important implications for geomorphic processes, hydrological balance, and human activities [3-5]. **In this context, we divided the global land surface into two major types: flat terrain and rugged terrain, which approximately correspond to the lowland and mountain categories described in [1,6].**

Moreover, to address the concern raised about the limitations of altitude banding, we revised the classification system. **In the updated version, we merged the previous second- and third-level categories within rugged regions, shifting the emphasis toward relative relief, in line with the reviewers' suggestions.** For flat regions, we retained elevation-based classification as recommended in previous studies, to better capture subtle variations within plains. We also updated the publicly available datasets to align with the revised classification system. **Additionally, in the data usage section, we have added a comparative analysis with runoff data [7], a key environmental factor related to surface hydrology, to demonstrate the applicability of the relief classes in ecological and hydrological studies.**

Furthermore, we have carefully revised the issues related to textual descriptions and figures throughout the manuscript. Corresponding updates have also been made to the related files in the data repository to ensure consistency with the revised content.

We sincerely hope that these revisions improve the rationality and clarity of the manuscript. Please refer to the detailed point-by-point responses for more information. Thank you very much for your thoughtful guidance and support.

[1] Viviroli, D., Kummu, M., Meybeck, M., Kallio, M., & Wada, Y. (2020). Increasing dependence of lowland populations on mountain water resources. Nature Sustainability, 3(11), 917-928.

[2] Meybeck, M., Green, P., & Vörösmarty, C. (2001). A new typology for mountains and other relief classes. Mountain research and development, 21(1), 34-45.

[3] Thornton, J. M., Snethlage, M. A., Sayre, R., Urbach, D. R., Viviroli, D., Ehrlich, D., Muccione, V., Wester, P., Insarov, G., & Adler, C. (2022). Human populations in the world's mountains: Spatio-temporal patterns and potential controls. PLoS One, 17(7), e0271466.

[4] Zhou, Z., & Chen, Y. (2025). How urban land expansion alters terrain in mountainous and hilly areas: An empirical study in China. Geography and Sustainability, 100304.

[5] Chen, Y., Yang, X., Fu, H., Li, C., & Tang, G. (2025). Characterizing spatial patterns and regionalization of anthropogenic landforms using multi-source geospatial data: Insights from Loess Plateau of China. Geomorphology, 478, 109708.

[6] Viviroli, D., Archer, D. R., Buytaert, W., Fowler, H. J., Greenwood, G. B., Hamlet, A. F., Huang, Y., Koboltschnig, G., Litaor, M.I., López-Moreno, J.I., & Woods, R. (2011). Climate change and mountain water resources: overview and recommendations for research, management and policy. Hydrology and Earth System Sciences, 15(2), 471-504.

[7] Sujud, L. H., & Jaafar, H. H. (2022). A global dynamic runoff application and dataset based on the assimilation of GPM, SMAP, and GCN250 curve number datasets. Scientific Data, 9(1), 706.

Reviewer #1

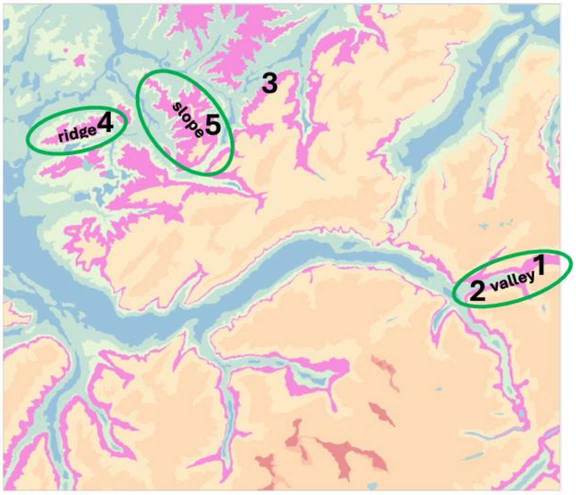
The comment in the email:
My original review was quite favourable because of the innovative way to delimit plains and mountains and how the problem of size of moving windows (NAW) on had been tackled. I commented that the calculated units did not represent landforms in my opinion, but rather slope and elevation classes. This point of view is not shared by the authors, but for me it is essential as I show in the report. The problem of mountain valleys classified as low hills persists, and some 'landform' categories regroup fundamentally different (convex - such as ridges - and concave - such as valleys -) shapes. The form aspect of the landforms is therefore not adequately captured in this classification, which basically represents units combining slope and elevation classes.

Comments in the attached PDF:
My original review was quite favourable because of the innovative way to delimit plains and mountains and how the problem of the size of moving windows (NAW) in neighbourhood analysis had been tackled. I commented that the calculated units did not represent landforms in my opinion, but rather slope and elevation classes within the three broad landform categories: plains, hills and mountains. This point of view is not shared by the authors, but for me it is fundamental as I show in the figure below.

The problem of mountain valleys classified as low hills persists, and some 'landform' categories regroup fundamentally different (convex - such as ridges - and concave - such as valleys -) topographical shapes. The morphological aspect of the 'landforms' is therefore not adequately captured in this classification, which basically represents units separating plains from hills (problematic, see below) and mountains, combined with slope and elevation classes. By focusing on the high precision of the result through the use of high resolution DTM, the product is of high precision of the mapping units but low accuracy of their classification in terms of landform. It would have been a good thing to validate the proposed landform classification with a number of experts, for example by extracting classified GBLU terrain units of a representative sample of small areas (e.g. 50 * 50 km, like in the figure shown below) and asking whether the proposed units resonated with their understanding of the landscape.

While acknowledging that the macro delimitation between plains and mountains (L1) is useful and based on an original approach, I doubt, as claimed, that anyone wishing to study erosion, microclimate or ecological zones locally or regionally would use the GBLU for these purposes, but rather stick to a DTM and derived measures such as ruggedness, slope, orientation etc. The proposed solutions to the concerns I advanced in my first reviews are purely cosmetic and do not address them fundamentally. I don't think for example that renaming 'mountain' to 'mountain slope' addresses the fact that the mapped units do not represent landforms. If you take a DTM and colour the elevation zones, the patterns you get are almost identical to the units of the GBLU. I don't see a clear advantage of using the GBLU over DTMs and elevation zones.

I am a bit challenged by the fact that the authors present a global landform map, but are fine with classifying a valley(floor) as a hill and then leave it up to the discretion of the users to reclassify their product to identify the actual landforms (such as valleys) they are interested in. If you look at the product and its classifications in a mountain region such as the Alps, the sequence of 'landforms' as one goes from low (valley bottom) to high (mountain peak) is: 1.0.1. (which does not figure in the legend, but I suppose it is 1.1.1.) low altitude plain (which would actually correspond to valley floor), 2.1.1., low altitude hill (which would actually correspond to valley or lower foot slope, depending on the width of the valley), 2.2.1. low altitude low relief mountain slope, 2.2.2. middle altitude low relief mountain slope, 2.3.2., 2.4.2., 2.5.2. and 2.5.3. These last classes mainly represent different elevation and slope classes on the slopes of a large mountain.



This figure from the Alps illustrates what is problematic from my point of view with the 'landform' classification proposed in the GBLU. The landform class 2.2.2. 'Middle-altitude low relief mountain slope', highlighted in purple, identifies lower slopes or valley bottoms (concave shapes) in the Alps while it identifies ridges (convex shapes) in the alpine foreland. Then, there is an intermediate case where 2.2.2. seems to correspond to mid-slopes of ridges.

Ontologically, morphologically, visually and genetically these landforms have very little in common, apart from a certain elevation and slope class. Basically, depending on where you look on the map class 2.2.2. is either a high mountain valley floor (1), a high mountain valley slope (2), a high mountain foot slope (3), a low mountain crest or ridge (4), or a low mountain slope (5).

I still like the innovations introduced to map plains and rugged terrain in great detail but I object to the presenting product's map units as representing landforms.

Response:

We sincerely apologize for not fully understanding your concern in the first-round revision. After receiving your valuable feedback, we conducted a thorough review of the relevant literature and carefully examined how different studies define and classify landforms or related geomorphic objects. In this revision, we made substantial adjustments to both the classification targets and the classification system.

First, we revised the terminology used to describe our classification targets. **In this study, our primary focus is on capturing morphological characteristics of the land surface, particularly the vertical variation and relief intensity across different landforms.** These features are highly relevant to ecological studies involving runoff and watershed dynamics [1,2], where similar units are often referred to as landforms (for example, the Global Landform Classification dataset provided by the European Soil Data Centre [3], which has the similar targets with our study). However, as you pointed out, these terms may not fully align with a strict geomorphological definition. **To address this issue, and following guidance from relevant literature, we have revised the terminology in our manuscript to refer to the results as *relief classes* rather than landforms.** This shift could reflect the nature of our classification while avoiding conceptual ambiguity. To further enhance clarity and practical value, we have added illustrations in the data usage section to demonstrate the applicability of our results. **We have expanded our discussion of how the derived relief classes can support ecological studies—particularly those focused on mountain-lowland runoff balance and water resource allocation.**

Second, we adjusted our classification terminology and system by referencing the Global Landform Classification dataset provided by the European Soil Data Centre (ESDAC), particularly the terminologies and system proposed by [3]. These changes were made in alignment with your suggestions and to ensure consistency with established international classification schemes.

Please refer to the detailed responses and revised manuscript for further clarification.

(1) Regarding the Classification Targets

In this study, our primary focus is on capturing morphological characteristics of the land surface, particularly the vertical variation and relief intensity across different landforms. However, as you pointed out, some of the units in our classification results may diverge from strict geomorphological terms in landform taxonomy. **Therefore, in light of your feedback and the further review of relevant literature [1-3], we acknowledge that the outcomes of our study are more appropriately aligned with the typology of relief classes.** Relief, as a fundamental component in shaping Earth surface processes, provides a more suitable conceptual basis for interpreting our classification results. The relief classes are significant in playing a critical role in regulating energy flows and material transport across terrestrial environments and exerting significant influence on geomorphic evolution, hydrological balance, and human activity [1,4,5]. The concept of relief emphasizes a terrain representation perspective, focusing on the overall morphological variation of the surface rather than referring to a specific relief index. In our study, AS (accumulated slope) is used to characterize surface roughness, while SRI (slope relief index) quantifies terrain undulation. Through methodological innovations in the calculation of both indices, we have achieved a more refined and accurate representation of relief features. This refinement forms the basis for our classification approach.

To support this interpretation, we have incorporated a comparative analysis between our classification results and global runoff data [6]. The comparison reveals a strong spatial consistency, especially in mountainous regions. As demonstrated in the newly added figures (Figure 1 in this file), both our classification and the runoff data exhibit similar spatial gradients and distribution patterns. We have added related explanation in the data usage section of the revised manuscript. Importantly, runoff reflects one of the key hydrological components of the Earth system. By providing more detailed and spatially refined relief classes, our study contributes knowledge that can help advance research in Earth system science, particularly where accurate terrain-based ecological zoning is critical. Given the relatively coarse spatial resolution (approximately 250 m) of existing global runoff datasets, we believe our classification could serve as a valuable base for runoff downscaling and related ecological modeling. Moreover, our classification results contain the ability to support ecological studies focused on hydrological supply-demand imbalances across mountainous and lowland regions such as the issue discussed in [1,7].

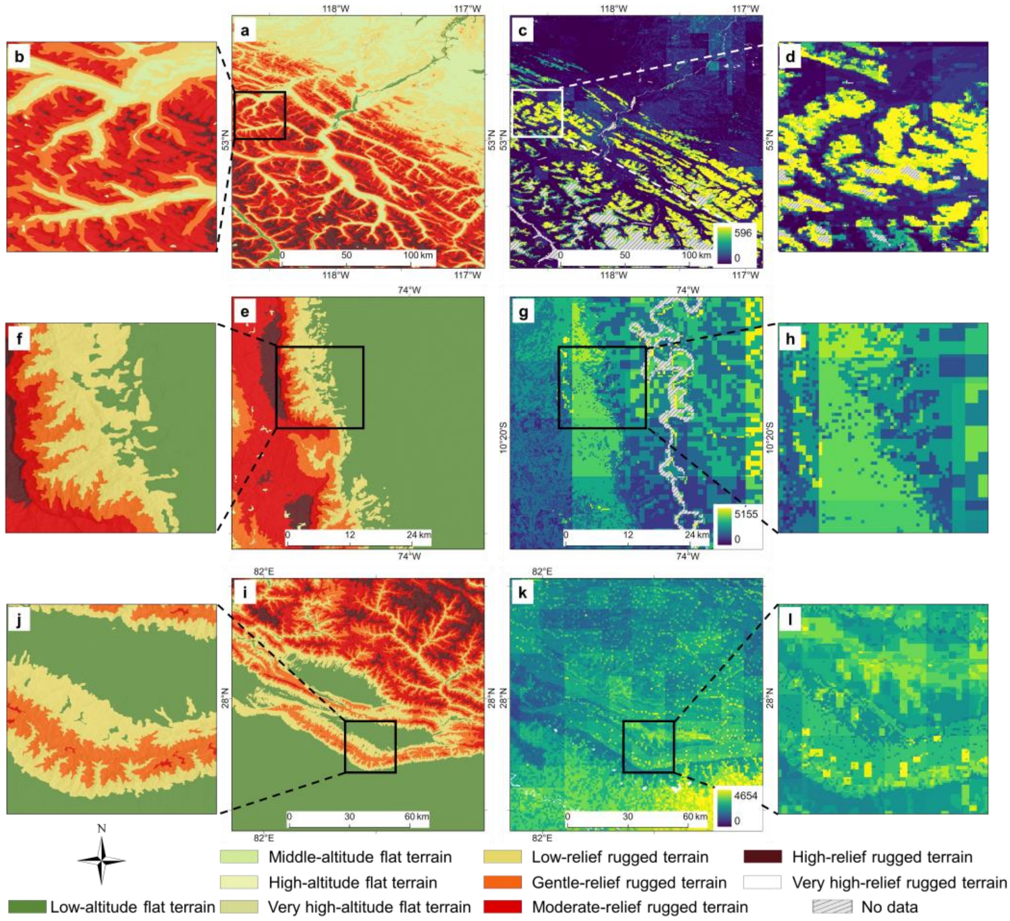


Figure 1. The spatial distribution of the global relief classes (GRC) and surface runoff in different areas. a and b show the GRC L2 for the Rocky Mountains in North America, while c and d display the corresponding runoff patterns in the same region. e and f show the GRC L2 for the Andes Mountains in South America, while g and h display the corresponding runoff patterns in the same region. i and j show the GRC L2 and runoff in the southern areas of the Himalayas, while k and l display the corresponding runoff patterns in the same region.

(2) Regarding the Classification System

In response to your valuable suggestion that traditional geomorphological terms such as plain, hill, and mountain may not precisely represent our derived units, we have revised the terminology to better reflect the actual properties of the classified surfaces. **We now adopt the terms "flat terrain" and "rugged terrain" to denote relatively smooth versus rough**

terrain, respectively. On this basis, we further subdivided the surface into multiple relief classes, as detailed in the manuscript. This revised terminology is more commonly used in ecological and climate-related research, where terrain relief rather than strict landform taxonomy is emphasized. We hope this terminology adjustment can clarify the nature of our classification results.

In response to your comments, as well as feedback from the second reviewer and insights from related literature, we have revised the classification scheme accordingly. **First, based on slope and AS, we divided the land surface into two major types: flat terrain and rugged terrain** (corresponding to the mountain and lowland categories described in [1]. Meanwhile, as you noted, introducing elevation-based classification—especially mountainous or rugged regions—can result in ambiguous or difficult-to-interpret units in the context of geomorphological or terrain-based research. Therefore, **in the revised manuscript, we merged the level 2 and 3 within rugged areas.** The updated classification in these regions now emphasizes relative relief, also aligning with the suggestion from Reviewer #2. **In flat regions, we retained elevation-based classification, as recommended by previous studies, to further differentiate plains.** As a result, the revised classification framework now includes two hierarchical levels, capturing the relief characteristics of the land surface in a more interpretable and practical manner.

Following these adjustments, we also updated the released classification dataset, and the associated data repository has been updated accordingly (https://doi.org/10.5281/zenodo.15641257).

Table 1. Classification of global relief.

L1	Code1	Colors (RGB)	L2	Code2	Colors (RGB)	Note
Flat terrain	1	129,168,0	Low-altitude flat terrain	11	90,138,55	Classifying L2 flat lad based on the altitude.
			Middle-altitude flat terrain	12	209,235,152	
			High-altitude flat terrain	13	237,242,179	
			Highest-altitude flat terrain	14	213,217,164	
Rugged terrain	2	255,255,190	Low-relief rugged terrain	21	230,216,106	Classifying L2 rugged lad based on the surface relief index.
			Gentle-relief rugged terrain	22	244,100,18	
			Moderate-relief rugged terrain	23	220,0,0	
			High-relief rugged terrain	24	86,20,24	
			Very high-relief rugged terrain	25	255,255,255	

(3) Regarding the Use of Classification Results and Quantitative Metrics

We acknowledge that quantitative metrics describing land surface morphology—such as slope, relief index, and curvature—are widely used across geomorphological and environmental studies. **However, in non-geomorphology domains，researchers may lack the technical background to interpret or transform continuous terrain indices into meaningful patterns.** Providing structured, interpretable relief classifications facilitates broader integration and discovery. In addition, directly using topographic indices in non-geomorphology domains may limit effective knowledge discovery as we also mentioned in the main text. For example, runoff estimation often relies on slope-based calculations, which can yield highly fragmented spatial outputs. In contrast, **relief classes offer a generalized representation that aligns better with ecological or hydrological zoning, enhancing interpretability and usability in downstream applications.** Therefore, we think that the availability of derived categorical data (i.e., relief classes) is also important, particularly for applications involving large-scale pattern recognition or interdisciplinary studies such as biodiversity, water sources, population distribution, or urban development [5,8,9].

[1] Viviroli, D., Kummu, M., Meybeck, M., Kallio, M., & Wada, Y. (2020). Increasing dependence of lowland populations on mountain water resources. Nature Sustainability, 3(11), 917-928.

[2] Viviroli, D., & Weingartner, R. (2004). The hydrological significance of mountains: from regional to global scale. Hydrology and earth system sciences, 8(6), 1017-1030.

[3] Meybeck, M., Green, P., & Vörösmarty, C. (2001). A new typology for mountains and other relief classes. Mountain research and development, 21(1), 34-45.

[4] Thornton, J. M., Snethlage, M. A., Sayre, R., Urbach, D. R., Viviroli, D., Ehrlich, D., Muccione, V., Wester, P., Insarov, G., & Adler, C. (2022). Human populations in the world's mountains: Spatio-temporal patterns and potential controls. PLoS One, 17(7), e0271466.

[5] Zhou, Z., & Chen, Y. (2025). How urban land expansion alters terrain in mountainous and hilly areas: An empirical study in China. Geography and Sustainability, 100304.

[6] Sujud, L. H., & Jaafar, H. H. (2022). A global dynamic runoff application and dataset based on the assimilation of GPM, SMAP, and GCN250 curve number datasets. Scientific Data, 9(1), 706.

[7] Viviroli, D., Archer, D. R., Buytaert, W., Fowler, H. J., Greenwood, G. B., Hamlet, A. F., Huang, Y., Koboltschnig, G., Litaor, M.I., López-Moreno, J.I., & Woods, R. (2011). Climate change and mountain water resources: overview and recommendations for research, management and policy. Hydrology and Earth System Sciences, 15(2), 471-504.

[8] Nogués-Bravo, D., Araújo, M. B., Errea, M. P., & Martínez-Rica, J. P. (2007). Exposure of global mountain systems to climate warming during the 21st Century. Global environmental change, 17(3-4), 420-428.

[9] Chen, Y., Yang, X., Fu, H., Li, C., & Tang, G. (2025). Characterizing spatial patterns and regionalization of anthropogenic landforms using multi-source geospatial data: Insights from Loess Plateau of China. Geomorphology, 478, 109708.

Reviewer #2

Review by Dr. Ian S. Evans of Durham University, of ESSD-2024-401
Global basic landform units derived from multi-source digital elevation models at 1 arc-second resolution, by Yang et al.

With a major computing effort, ~90 m DEMs are processed globally (82ºN to 88ºS) to outline landform areas at three levels (2, 6 and 23 classes). Initially a dichotomy is mapped: plain cores with slopes of below 1.5º to 3º are extended along traverses until 'accumulated slope' exceeds a threshold. This defines the division between plains and mountains. At a second level, 'mountains' are divided into 5 surface relief classes, of which the lowest is redefined as 'hills'. In level 3, these 6 classes are subdivided into 23 on the basis of 4 elevation or relief bands. (Perhaps some of this more precise description could be included in the abstract.)

Response: Thank you for your valuable comments. We have revised the abstract to include more specific details as suggested. We would also like to clarify that the base DEM used in this study is the 1 arc-second resolution (~30 m), not the 90 m resolution as mentioned.

The global results in Fig. 4 produce familiar patterns, in which level 2 essentially maps relief. The only strange aspect is that both ice sheets are mapped as plains, with the narrowest of 'hill' fringes. The complexity of the level 3 map is quite rightly explored in detailed extracts in Figs. 5 – 8. In Fig. 5, c successfully distinguishes hills from plains, but some boundaries in 5d, e, f and g (and Fig. 6) resemble elevation contours rather than landform boundaries. In Fig. 7 there are huge differences between K1, K2 and K3 for the Andes, that are difficult to understand: K3 seems to produce reasonable results for the Alps and Himalayas. In Fig. 8c the area mapped as 'hills' is a thin rim around the mountains – a 'mountain fringe' rather than hills.

Response:

Thank you for your insightful suggestion. **Another reviewer raised a similar concern, noting that our classification targets may differ from strictly defined geomorphological landform units.** In this study, our primary focus is on capturing morphological characteristics of the land surface, particularly the vertical variation and relief intensity across different landforms. These features are highly relevant to ecological studies involving runoff and watershed dynamics [1], where similar units are often referred to as landforms. **After carefully considering the reviewers' comments and conducting a further review of relevant literature, we acknowledge that the outcomes of our study are more appropriately aligned with the typology of *relief classes* [1,2]**. Relief, as a fundamental component in shaping Earth surface processes, provides a more suitable conceptual basis for interpreting our classification results. his shift more accurately reflects the nature of our classification while avoiding conceptual ambiguity. Meanwhile, to further enhance clarity and practical value, we have added illustrations in the data usage section to demonstrate the applicability of our results.

In addition, following the adjustment of classification targets, we have also addressed the concern you raised regarding the use of the term "hill" and "mountain," which may not precisely represent the derived units. Drawing on previous literature [2], we have revised the terminology to better reflect the actual properties of the classified surfaces. Specifically, **we**

now adopt the terms "flat terrain" and "rugged terrain" to denote relatively smooth and rough terrain, respectively. Based on this framework, we further subdivided the surface into multiple relief classes, as detailed in the revised manuscript. This revised terminology is more commonly used in ecological and climate-related research, where terrain relief rather than strict landform taxonomy is emphasized. Furthermore, we have revised our classification system (as detailed in the following response) to improve the rationality and clarity of the classification results. **In addition, we have added descriptions of K1, K2, and K3 in the manuscript to explain the underlying reasons for their differences.** We also agree with your observation that K3 appears to produce reasonable results for the Alps and Himalayas. As shown in Figure 7, our classification exhibits a distribution pattern broadly consistent with K3, while offering improved accuracy in delineating mountainous boundaries.

Following these adjustments, we also updated the released classification dataset, and the associated data repository has been updated accordingly (https://doi.org/10.5281/zenodo.15641257).

[1] Viviroli, D., Kummu, M., Meybeck, M., Kallio, M., & Wada, Y. (2020). Increasing dependence of lowland populations on mountain water resources. Nature Sustainability, 3(11), 917-928.
[2] Meybeck, M., Green, P., & Vörösmarty, C. (2001). A new typology for mountains and other relief classes. Mountain research and development, 21(1), 34-45

The authors must be congratulated on solving the various technical problems in processing a huge combined data set and defining classes that require minimal human editing. The most controversial aspect is the emphasis in level 3 on elevation. This is consistent with the declared aim to be relevant to ecology and human geography. It does mean that the units are bioclimatic as well as geomorphological. A plain is a plain and a drumlin a drumlin whether at 50 m or 4000 m: thus the elevation banding does not give information on landforms. See also Fig. 6e1 comment below.

Because of this, the results may be of more interest to ecologists than to geomorphologists. There should at least be some recognitions of the limitations of using altitude bands within a landform classification.

The Iwahashi classifications produce more complicated patterns, but by using slope, dissection, sinks and terraces they do seem to relate more closely to landform characteristics. From your three levels, I prefer the level 2 to the level 3 result. Alternatively an altitude map and a relief map can be juxtaposed or superimposed.

Response:

Thank you for your valuable suggestion. After carefully reviewing your comments and reanalyzing our results, **we agree that incorporating altitude as a classification criterion may introduce certain limitations.** As noted in our previous response, the primary focus of this study is to characterize the vertical variation and relief intensity across different land surfaces. In response to your comments, as well as feedback from the first reviewer and insights from related literature, **we have revised the classification system accordingly.** First, **based**

on AS, we divided the land surface into two major types: flat terrain and rugged terrain (corresponding to the mountain and lowland categories described in [1]). Meanwhile, as you noted, introducing elevation-based classification within rugged areas—especially mountainous regions—can result in ambiguous or difficult-to-interpret units in the context of geomorphological or terrain-based research. Therefore, **in the revised manuscript, we have merged the level 2 and 3 within rugged areas.** The updated classification in these regions now emphasizes relative relief, aligning with the suggestion from you. **In flat regions, we retained elevation-based classification, as recommended by previous studies [2,3], to further differentiate plains.** As a result, the revised classification framework now includes two hierarchical levels, capturing the relief characteristics of the land surface in a more interpretable and practical manner. To further enhance clarity and practical value, we have added illustrations in the Data Usage Note section to demonstrate the applicability of our results. We expanded our discussion of how the derived relief classes can support ecological studies—particularly those focused on mountain-lowland runoff balance and water resource allocation.

[1] Viviroli, D., Kummu, M., Meybeck, M., Kallio, M., & Wada, Y. (2020). Increasing dependence of lowland populations on mountain water resources. Nature Sustainability, 3(11), 917-928.
[2] Meybeck, M., Green, P., & Vörösmarty, C. (2001). A new typology for mountains and other relief classes. Mountain research and development, 21(1), 34-45
[3] Zhou, C. H., Cheng, W. M., Qian, J. K., Li, B. Y., & Zhang, B. P. (2009). Research on the classification system of digital land geomorphology of 1: 1000000 in China. Journal of Geo-Information Science, 11(6), 707-724.

DETAILS:
Line 1 As ‘models’ is plural, perhaps ‘multi-source’ is unnecessary.
Response: We have removed ‘multi-source’.

20 ‘classified landform data’ [arguably the DEMs are landform data, so ‘lacking’ reads strangely.]
Response: We have changed it to ‘classified relief and landform data’. (Line 22)

27 ’26 classes’ is mentioned here, but never below. In fact Figs. 4, 5 and 6 and Table A1 show 23 classes, as stated in line 242.
Response: Thank you for your suggestion. Although the classification system allows for 26 potential classes, three of them are not observed in practice. Therefore, only 23 classes were presented in the figures and tables. In this revision, we have updated the classification system and eliminated this inconsistency accordingly.

29 Not ‘novel’; just expressed here more precisely than before. (We all knew that the Chinese P.R. incorporated very varied landforms).
Response: We have changed it to ‘finer and more precise spatial disparities in landform patterns than before’. (Line 31)

30 ‘Peru and China’ ? (cf. Fig. 9c)

Response: We have changed it to ‘Peru and China’. (Line 32)

43 Delete ‘the’

Response: We have removed ‘the’ in this sentence.

64 ‘most previous’

Response: We have changed it according to your comment. (Line 31)

71 ‘increased the complexity of’ … ‘that poses’.

Response: We have changed this sentence according to your comment. (Line 67)

106 Insert ‘based on slope’.

Response: In the revised manuscript, this sentence has been removed due to the modifications made to the classification scheme. To address your concerns, we have added new statements and incorporated the corresponding descriptions as suggested: “In this study, we refer to the two primary surface types as flat terrain and rugged terrain, based on their differences in slope characteristics.” (Lines 110-111)

110 NO: Fig. 4 contradicts this. Plains are subdivided only in level 3. Therefore on –

Response: We revised this sentence to “At L2, the flat terrain retains elevation-based characteristics and is further divided into low-altitude, middle-altitude, high-altitude, and very high-altitude flat terrain.” (Lines 116-117)

112 ‘plains, hills and mountains…’

Response: This sentence has been removed in the revised manuscript.

121 Omission: REMA must be mentioned / defined.

Response: Reference Elevation Model of Antarctica (REMA) and its citation [1] have been added in this paragraph. (Line 126)

[1] Howat, Ian, et al., 2022, “The Reference Elevation Model of Antarctica – Strips, Version 4.1”, https://doi.org/10.7910/DVN/X7NDNY, Harvard Dataverse, V1.

144-149 This could be better expressed. ‘Transitions have plain cores…’ is confusing: transitions are AROUND cores; transitions contain small areas of steeper slopes… The sentences ‘Misclassifications…’ and ‘Meanwhile …’ are too vague to be meaningful.

Response: We have changed this sentence to “Transitions occur around cores and contain areas with higher slope than typical flat terrain” (Lines 156-157). Meanwhile, the following two sentences have been changed to “In this context, misclassification tends to occur in transitional zones, which exhibit mixed topographic features that do not fully align with either flat or rugged terrain characteristics.” (Lines 161-162) and “The boundary is defined as the spatial margin of flat terrain where topographic properties and classification labels shift gradually toward those associated with rugged terrain.” (Lines 159-161)

149 Delete ‘the’

Response: ‘the’ has been removed in the revised manuscript.

161-166 These very general sentences surely should come earlier?

Response: As you suggested, these sentences are indeed better placed earlier in the section. Therefore, we have reorganized Section 2.2.2 accordingly. Specifically, the original content from lines 161–166 has been merged into the first paragraph of this section to clarify the overall conceptual design of the ontology-based method. In the second paragraph, we focus on the specific implementation of this approach using quantitative terrain factors.

168 ‘very low relief’ – but defined by slope, above.

Response: We originally used the term relief to characterize surfaces with relatively flat and low-undulating morphological features. In the revised manuscript, we have added ‘slope’ in this sentence to clarify our idea. (Line 156)

169 ‘containing’ But a better expression of lines 168-169 is ‘with elements steeper and others flatter than the threshold slope.’

Response: Thank you for your suggestion. As mentioned earlier, we have reorganized the content of Section 2.2.2. In the revised version, the original sentence has been merged into another sentence “Transitions occur around cores and contain areas with higher slope than typical flat terrain, i.e. areas that in part satisfy their classification as flat terrain but also exhibit sloping characteristics not typical of flat terrain. In a general geographic context, these areas should also be classified as flat terrain.” (Lines 156-158)

169-171 Another two vague, uninformative sentences. What proportion of the transition area can have non-plain slopes, before it is excluded from ‘plain’? 172-178 does not clarify this. The boundary is eventually drawn at the T2 threshold but what are the consequences of that for what is eventually labelled ‘plain’?

Response: In the revised manuscript, we have reorganized Section 2.2.2 to improve clarity. First, we added a statement in the first paragraph to better explain the relationship between transition areas and plain cores: “In a general geographic context, these areas should also be classified as flat terrain. However, current methods that emphasize local topographic characteristics often fail to identify them correctly” (Lines 158-199). Second, after determining the T2 threshold, regions with AS values lower than T2 are defined as transition areas. These are subsequently merged with the plain cores to form a complete plain unit. We have added further explanation of this process in the revised version to enhance understanding: “Areas where the AS value is less than T_{AS} are merged with the cores to form the complete flat terrain, while the remaining areas are classified as rugged terrain.” (Lines 192-193)

181 ‘typical area extracted’

Response: We have revised this sentence to “the core is as extracted in the previous step”. (Line 181)

192 what are the units?

Response: The AS index is a dimensionless quantity, therefore there is no unit.

It seems T1=Tss and T2=Tas – so why are both versions necessary?

Response: In the revised manuscript, we have renamed T_1 and T_2 to T_{SS} and T_{AS}, respectively, to maintain consistency in terminology throughout the text.

194 What was the area of the largest island that required human intervention? Is this the only part of the process that required human intervention, or does variation of the slope threshold between 1.5 º and 3º also require such?

Response: In this study, based on our preliminary experiments, we identified that islands with an area smaller than 36 km^2 require human intervention to ensure accurate classification. Aside from the desert regions already discussed in the manuscript, these small islands are the only areas where manual intervention was necessary. Additionally, we carefully re-examined our experimental procedures and confirmed that the current classification results were all generated using a slope threshold of 1.5 degrees. We apologize for the earlier oversight in describing this aspect. In the revised manuscript, we have added explanations addressing both of these issues to clarify our methodology.

198-199 Only one 'novel', please… delete first.

Response: We have deleted it.

215 colon rather than comma after 'limitations'.

Response: We have changed it as your suggestion.

217 delete second 'method'

Response: We have deleted it.

217 'which does not'

Response: We have changed it as your suggestion. (Line 217)

218 'relief relative …'

Response: We have changed it as your suggestion. (Line 218)

222 'for objectives' … 'mountain climate' .

Response: We have revised it as your suggestion. (Line 222)

229 '3c), we' … 'features,'

Response: We have revised it as your suggestion. (Line 229)

233 'Specifically, we construct …'

Response: We have revised it as your suggestion. (Line 233)

240 Not "For the plains," but 'For both plains and mountains,'

Response: Thank you for your valuable suggestion. In the revised manuscript, we have adjusted the classification system. Currently, only the flat terrain (formerly referred to as "plain") is classified based on elevation. Accordingly, we have revised the original sentence to specify "for flat terrain" to improve accuracy and clarity.

241 I would describe these as ‘classes’, rather than landforms.
Response: We have revised it as your suggestion. (Line 241)

241 “Mountains are classified as hill, low-relief, middle-relief, high-relief, and highest-relief mountains, based on threshold SRI values of 200m, 1000m, 3500m and 5000m.” belongs in the previous section – line 237?
Response: In the revised manuscript, we have restructured the content accordingly. Section 2.2.3 (originally around line 237) is now dedicated to quantifying surface relief in the rugged terrain and does not involve specific Level-2 classification thresholds. All threshold values and classification criteria are now presented in Section 2.2.4 to improve clarity and coherence

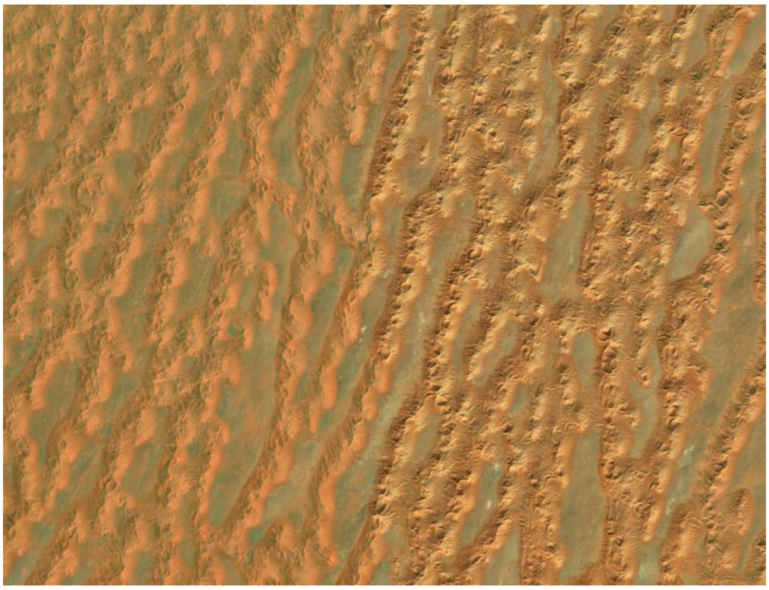
255-269: this does not seem to cope with the altitude banding problem identified below in Fig. 6e1.
Response: As you pointed out, the altitude banding problem may not be fully resolved at this stage. In desert regions, our primary concern is the limited applicability of the previous method. The optimization steps described in this section are mainly designed to extract accurate feature lines to support the calculation of the surface relief index. We have provided a more detailed explanation in our response to your comment regarding Fig. 6e1 below.

Fig.4: What is the projection? Unfortunately it is not equal-area …
Response: We have changed it to an equal-area projection ‘Equal Earth’ (EPSG: 8857).

283 Delete ‘the’
Response: We have deleted this word.

286 ‘underscores’
Response: We have revised it as your comment. (Line 285)

Fig.5 (see general comment.) Also, why is one side of each dune grey, the other yellow? This cannot be altitude, it mimics the illumination (hill shading) effect seen in the remote sensing image. How can relief vary so much between one side of a dune and the other?
Response: The grey and yellow tones observed in Figure 5 are not caused by hill shading effects, but rather reflect the actual color differences of the sand surface captured in the remote sensing imagery. These two color variations do not indicate the two sides of a dune, but instead represent distinct geomorphic units—dunes and interdune areas. As illustrated in the figure below, which corresponds to an adjacent area of Figure 5c, the imagery has not been mosaicked, and thus lighting conditions should be consistent. By comparing with the right-hand side of the image, we can observe that shadows are expressed as dark or black areas, not grey or yellow. Therefore, the "various relief between one side of a dune and the other" mentioned in the comment more accurately reflects the relief between dune crests and interdune flats.



292 Column heading with 'dataset (90 m)' should be 'Iwahashi & Yamasaki' … not et al.
Response: We have revised it as your comment. (Line 291)

Fig. 6e1 Why do dunes have a dark brown core, surrounded by a pale brown shade? This distinction seems to arise from an altitude contour intersecting at mid-dune. If so, that is pretty meaningless in terms of classifying landforms: each dune is a single landform. (Presumably the pale green represents inter-dune corridors.)
Response: As you pointed out, dunes should be treated as a single and continuous landform. In our Level-1 classification, we aimed to preserve this integrity by distinguishing between dune and interdune areas. We agree that introducing elevation bands may fragment the dune structure. Therefore, in the revised manuscript, we merged elevation and relief information to reduce the adverse effects of altitude-based segmentation. After this revision, we observed that some fragmentation issues still persisted in certain regions. In the updated classification, the segmentation is primarily based on the SRI (Surface Roughness Index), and the classified results could be referred to dune ridges, slopes, and interdune zones. In the revised manuscript, we have added a description of this limitation, acknowledging that the proposed method may, in some cases, generate landform units that do not fully preserve geomorphological completeness.

313 What is the difference in construction of K1 and K2, if both are based on 1000 m resolution DEMs? The coarse resolutions (even the 250 m K3) make comparisons with GBLU's 30 m dubious.
Response: K1 was developed for mapping global mountain forests, where mountainous areas are identified based on whether the combined values of elevation, slope, and ruggedness (or relative relief) exceed predefined thresholds. In contrast, K2 was designed to facilitate mountain biodiversity comparisons and adopts a similar approach, but uses ruggedness as the sole classification criterion.

As you rightly noted, there is a resolution difference between K3 and our results. However, the selected dataset K3 currently represents the highest-resolution global dataset available for mountain classification, and thus serves as the most suitable reference for comparison. To further evaluate the reliability of our dataset, we also compared it with other higher-resolution landform and terrain classification results at different scales. We think that the combination of these comparisons provides a comprehensive validation of our classification outcomes.

300 ‘Meanwhile valley-like objects’
Response: We have revised it as your comment. (Line 299)

337 Some plains (alluvial) are really flat. They must be much less than 70% of land area. Distinguishing these might be more useful than using a purely altitude-based division of plains.
Response: As you pointed out, distinguishing plains—especially alluvial plains—is essential. Our team has been exploring methods to extract such features, including recent work (e.g., Sun et al. 2025). However, considerable challenges remain when addressing global-scale classifications. We hope that in future work, by incorporating additional data layers into the current dataset, we can further refine the classification to distinguish genetically meaningful units such as fluvial/alluvial plains.

Sun, W., Chen, Y., Zhou, X., Yang, X., Ma, J., Li, S., & Tang, G. (2025). Understanding the hydrological valley landscape: A multi-scenario adaptive framework for delineating valley floors. Catena, 256, 109111.

351 This heading is uninformative. The section deals with ‘Geographic relationships: climate and land use’.
Response: According to your comment and the new experiment, we have changed the heading of this section to ‘Geographic relationships: runoff, climate and land use’. (Line 343)

352 ‘relationships’
Response: We have revised it as your comment. (Line 350)

364 This is mainly due to ice sheets ! They should be considered separately.
Response: Thank you for your valuable comment. We have included additional explanations in the manuscript to highlight the distinct characteristics of this region and to clarify the special influence of ice sheets on surface elevation and relief patterns. (Lines 372-375)

391-392 Only one ‘novel’, please… delete second?
Response: We have revised it as your comment.

Table A3 Two names are uninformative or inaccurate:
‘Great Socialist People’ is ‘Libya’. The full name is ‘State of Libya’.
Checking where ‘ Democratic People’ might be, I find that DZA is ‘Algeria’.
Response: We have checked these names and revised these mistakes.