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Hydrology and Earth System Sciences Discussions

Interactive comment on "Land classification based on hydrological landscape units" *by* S. Gharari et al.

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A new landscape classification: the HAND Model

The HAND model introduction, the theory and thorough validation of the HAND based landscape classification at Journal of Hydrology

In the context of this Discussion Paper (DP) [Gharari et al. 2011] it became necessary to post a few relevant excerpts from the HAND publications. These excerpts are not substitutes for the full content in the respective papers, but highlight the passages

that have direct interest to this discussion. Please see also the history of the HAND development posted in this discussion [Nobre, 2011].

It is important and useful to separate citation of the HAND papers. Rennó et al (2008) was aimed to the remote sensing community, it presents the HAND computational tool (or algorithm), and a preliminary landscape classification (for the Asu catchment only). Nobre et al (2011) was aimed to the hydrological community, presenting and formally introducing the HAND model, its physical fundaments and a complete HAND-based landscape classification, with clear definitions of terrain classes, their calibration and validation. The data for landscape classification presented in both Rennó et al (2008) and Nobre et al (2011) is one and the same, so a much more informative and useful referral to the data is Nobre et al (2011). Although Rennó et al (2008) is a better citation for the algorithm itself, with its mathematical formalization, it is not the best citation for the data nor to the HAND-based landscape classification.

Selected Excerpts from

Nobre, A.D., Cuartas, L.A., Hodnett, M.G., Rennó, C.D., Rodrigues, G., Silveira, A., Waterloo, M., Saleska, S. 2011. Height Above the Nearest Drainage - a hydrologically relevant new terrain model. ***Journal of Hydrology*** 404, 13–29.

Title: . . . Height Above the Nearest Drainage – **a hydrologically relevant new terrain model**

Summary: This paper introduces a new terrain model named HAND, and reports on the calibration and validation of landscape classes representing soil environments in Amazonia, which were derived using it.

The HAND model normalizes topography according to the local relative heights found along the drainage network, and in this way, presents the topology of the relative soil gravitational potentials, or local draining potentials.

The HAND model has been demonstrated to show a high correlation with the depth of the water table, providing an accurate spatial representation of soil water environments.

Normalized draining potentials can be classified according to the relative vertical flowpath-distances to the nearest drainages, defining classes of soil water environments.

These classes have been shown to be comparable and have verifiable and reproducible hydrological significance across the studied catchment and for surrounding ungauged catchments.

The robust validation of this model over an area of 18,000 km2 in the lower Rio Negro catchment has demonstrated its capacity to map expansive environments using only remotely acquired topography data as inputs.

The classified HAND model has also preliminarily demonstrated robustness when applied to ungauged catchments elsewhere with contrasting geologies, geomorphologies and soil types.

The HAND model and the derived soil water maps can help to advance physically based hydrological models and be applied to a host of disciplines that focus on soil moisture and ground water dynamics.

As an original assessment of soil water in the landscape, the HAND model explores the synergy between digital topography data and terrain modeling, presenting an opportunity for solving many difficult problems in hydrology.

1 Introduction

. . .if parameter calibration could somehow be solved for large areas, the capacity to produce a generalized deterministic treatment of surface water dynamics could represent a great advance.

However, to our knowledge, no landscape-scale normalization of topography, with relevance to the understanding of soil water dynamics, has been attempted. We aimed at developing a model able to make contrasting catchments, at the hillslope flowpath level, uniformly comparable.

In this paper we present a new terrain model called Height Above the Nearest Drainage (HAND) that normalizes DEMs according to distributed vertical distances relative to the drainage channels.

We classified the HAND model according to soil environments and calibrated the classes for the Asu catchment . . ., **mapping soil environments at its small scale** (13 km2).

Finally we validated **those HAND classes** for a larger encompassing region in the lower Rio Negro region of central Amazonia, **mapping soil environments at two additional scales** (500 km2 and 18,000 km2).

2 The HAND Model

The second and original set of procedures uses local drain directions and the drainage network to generate a nearest drainage map, which will ultimately guide the HAND operator spatially in the production of the normalized topology of the HAND model.

3 Finding significant HAND classes

Based on the normalized distribution of relative gravitational potentials, **we report here the quantitative capacity of the HAND model to reveal and predict hydrologically relevant soil environments.**

The HAND model output of normalized heights is classified into HAND classes, which are defined based on field data or knowledge of local terrain, thus generating maps of soil environments (Fig. 3).

[SEE FIGURE 3]

Fig. 3. Procedure to generate a HAND map of environments: (a) applying onto the HAND model a classification criteria, with the range of heights in each terrain class defined by the map's purpose, results in (b) a HAND map of environments.

3.1 Study site and methods

The calibration and validation of the HAND classes were done in a large area in central Amazonia. . .

To acquire field data for calibration, we visited 120 points in the Asu catchment (Fig. 6), and another 90 points were visited for validation in several catchments across the lower Rio Negro region.

Contrasting non-floodable local environments were identified in the field through hydrological data and cues in the topography, vegetation and soils.

3.2 Defining soil environments

The hydrological transect (Fig. 6, site C1), running orthogonally from the second-order Asu stream to the top of the plateau (Fig. 7), represented all of the topographic features in the area, and contained the sampling points for vegetation, soil, soil–water and topography.

Four broad and contrasting categories of terrain, or soil environments, were found for this catena: (a) near the stream, soils were **waterlogged**, meaning that the water table level is always at, or very close to, the surface, creating an almost permanent swamp; (b) moving away from the stream, the ground surface rises gently above the water table over a transition zone, or **ecotone**, where the vadose zone extends up to a depth of approximately 2 m; (c) further away from the stream, the landscape rises quickly, forming a steep **slope**, with the vadose layer becoming progressively dominant in the soil environment; (d) at the farthest distance from the stream, along the catchment divide, the landscape levels out into a **plateau**, with a vadose layer thicker than 30 m.

3.3 Defining HAND classes

A HAND terrain class is here defined as a range of vertical distances to the nearest drainage reference level that bears roughly uniform hydrological relevance.

3.3.1 Calibrating HAND classes

The calibration of HAND classes consisted of matching field-verified environment types with the corresponding distribution of heights in the HAND model (Fig. 8).

The height distribution for the field verification points in the Asu catchment indicates that the normalized relative gravitational potential in the HAND model is an effective topographical parameter in the separation of local environments, especially for water-logged from ecotone and upland classes.

3.3.2 An auxiliary class

Although the upland class, which encompasses both flat and sloping terrain (plateau and slope), represented well the soil water condition (well drained, relatively deep water table) and in a relatively homogeneous way in comparison to the other two lowland classes, there are quite significant and distinct hydrological behaviors that set slopes and plateaus apart. . . . Here slope angle will be an auxiliary independent separator applied exclusively for the upland HAND class.

3.3.3 Calibration results

Using these field-optimized thresholds, we classified the HAND model into four classes. The field verification survey was accurate in identifying the local soil environment for each chosen point. Overlaying the field verification points onto the HAND classes (Fig. 10) reveals how well the HAND classification fared. For most points, the matching between field environments with HAND-predicted environments was good.

This comparison suggests a coherent matching between field-identified local environments, corroborated by groundwater data, with the classified HAND topology.

3.4 Height frequency histograms

Height above sea level frequency distributions for the HAND classes were computed by overlaying the spatial masks for each HAND class (normalized) onto the SRTM-DEM (non-normalized). The overlap of elevations of the four contrasting environments,

when seen on the actual topography, explains why height above sea level is unable to discriminate local environments properly.

This analysis reveals that the normalized relative gravitational potential in the HAND model is a good parameter for the definition of relevant and distinct classes of stationary soil water conditions.

The non-overlap of contrasting environments in the HAND topology indicates that the HAND classes are able to discriminate local environments properly.

3.5 HAND and water table

The correlation of water table depths (long-term data from 27 piezometers) with HAND model heights (y = 0.658x - 2.89 R2 = 0.806) indicates that the water table follows local normalized topography well.

To probe the relationship of water table depth with HAND heights beyond the low-density sampling of the piezometer network, we employed a simulated water table generated by Cuartas et al. using the DHSVM hydrological model. . . . The distributions are bi-modal, as is the frequency distribution of height above nearest drainage in the HAND model (Fig. 12).

The quantitative analysis (Fig. 14) showed a satisfactorily good validation for the three HAND classes, considering the same class thresholds adjusted in the calibration. This finding indicates that the classified HAND model is able to remotely estimate local environments. . . with good confidence.

4 Validation

To test the robustness of the calibrated HAND classes (i.e., the ability to fit landform patterns with soil water conditions for ungauged catchments) we validated it for distinct terrains.

4.1 Large-scale validation through mapping

We have applied the classified HAND model using .... elevation data for mapping forested areas of central Amazonia, analyzing its capacity to map soil water environments beyond the local scale of the Asu calibration, at two additional scales.

4.1.1. 500 km2

The HAND model creates hydrological/terrain homogeneity within and with the drainage network, but it still lacks a useful quantitative description of the landscape. **Classifying the HAND model into classes produces a map of terrain/hydrological character that can be used as an accurate and quantitative data source for landscape studies (Fig. 17).**

Besides the geographical location given by the HAND classes map, the respective areas occupied by the terrain types or distinctive soil–water environments can now be accurately accounted for (Table 1).

4.1.2. 18000 km2

The classified HAND model reveals an extraordinary richness of local environments (Fig. 22). Features that could not be seen in the HAND model alone become apparent, such as the areal extension of particular terrains or mosaic combinations of local environments and even signs of geomorphologic evolution. Variations in the slope and plateau classes on the opposite banks of the large river reveal interesting patterns.

In the frequency histogram of the HAND model (Fig. 24), the classes are again completely separated. The HAND histograms for the three areas indicate that the larger the area considered, the smoother the distribution.

The HAND model, calibrated using data from the Asu catch- ment, revealed good correlations between local environments and HAND classes and has been demonstrated to be robust during validation for the encompassing larger region.

Additional and preliminary validation made in remote areas of Brazil (São Gabriel da Cachoeira, Balbina and Urucú in Amazonas State; eastern São Paulo State; Rio de Janeiro State; and independently by Collischonn (2009) at the upper Tapajós river in Pará State and Grande Sertão Veredas in Minas Gerais State) **has further corroborated the ability of the HAND model to remotely predict local saturated areas of ungauged catchments**, irrespective of quite contrasting associations of geomorphology, soils and vegetation.

4.2 HAND vs TWI

We tested the similarity between HAND heights and the TWI for the entire dataset encompassing our Rio Negro study area (excluding drainage cells and cells neighboring the divide), finding no significant correlation between the two variables (Fig. 25).

5 Discussion

5.1 ...

5.2 Calibration and validation

Rigorously, the normalized topology of the HAND model is not directly about soil–water. The gravitational potential is a positional property of the landscape, a physical force that submits any water on and in the terrain to downward acceleration. Because under such force water infiltrates into the porous media (if it is not saturated) or moves downhill on the surface as runoff, draining to the stream, we equated the relative gravitational potential to a draining potential, that is, the net capacity for water to drain from its position on the hillslope to the nearest drainage channel.

High HAND heights mean large draining potential, where water will drain effectively leading to the appearance of a vadose zone; low HAND heights mean low draining potential and proximity to the water table, where draining water will pool, creating waterlogging.

The convincing association of terrain types with distinctive HAND height-classes made in the calibration, and widely corroborated by the validation, demonstrated that the relative gravitational potential in the HAND model has a very high correlation with soil–water saturation regimen. The depth of the saturated zone conditions superficial soil–water environments.

Even though the soil–water calibration for the HAND classes was conducted in a small gauged catchment, the validation covered thousands of square kilometers of very heterogeneous terrain, all with ungauged catchments. The consistency of the HAND classes' thresholds for a variety of verified terrains, especially the 5 m indicating superficial saturation, was an extraordinary finding of this study. This suggests the im-

portance of the local draining potential in shaping the soil–water saturation regimen, determining the depth of the water table. The non-arbitrary deterministic nature of these thresholds seems to be supported by a generalizable physical principle.

It appears that such landscape-scale control of saturation regimen is the driving factor influencing vegetation cover, soil genesis and geomorphologic evolution. Correspondence of the HAND environments with landforms, landcover and other landscape characteristics, allows for the construction of a variety of HAND-based feature maps.

5.3 Relative Topography

All of these studies [referring to the literature review on the matter] have directly or indirectly recognized the importance of relative local terrain distances as landscape variables influencing soil water dynamics. However, to our knowledge, no published work has set the stream channel as the base reference height against which all other flowpaths should be normalized. Provided that the stream network is well defined, the HAND model heights have uniform and universal hydrological significance.

5.4 Applications

The terrain normalization that we report here can be applied to DEMs of any terrain, generating HAND models with implicit geo- morphologic, hydrological and ecological relevance.

The significance of such terrain normalization for practical applications can be seen by calibrating HAND classes to match relevant soil water and land cover characteristics.

The application of the HAND model provides the possibility of capturing and examining heterogeneities in local environments in a quantitative and widely comparable manner.

Thompson et al. (2001) listed three key factors for soil genesis/landscape modeling:

representation of the continuous variability of soil properties across landscapes; relating of environ- mental factors to topography; and making spatial predictions of soil properties for unsampled locations. The HAND model offers spatially optimized and physically substantiated solutions for all three factors.

Surface hydrology could benefit from the availability of soil parameter layers, which can be derived from accurately classified HAND models.

Large-scale remote mapping of the soil moisture character, a crucial demand of advanced Earth System models (e.g. Koster et al., 2004), can be made feasible through the application of the HAND model to expansive areas without losing the information from low order catchments.

The portfolio of applications for this new terrain model is likely to grow as different communi- ties come to require knowledge of meaningful, contrasting and generalizable stationary hydrological properties of terrains at a fine local scale.

6 Conclusions

The height above the nearest drainage model is a drainage normalized version of a digital elevation model. The z axis variable of the HAND model is the normalized local height, defined as the vertical distance from a hillslope surface cell to a respective outlet- to-the-drainage cell, i.e., the difference in level between such cells that belong to a mutually connecting flowpath.

The field testing of the HAND model, conducted in an instrumented hydrological catchment and on surrounding terrain in Amazonia, **revealed strong and robust correlations between soil water conditions and the segmented classes in the HAND topology.**

This correlation is explained by the physical principle of the local gravitational potential,

or relative vertical distance to the drainage, which we called local draining potential.

Provided that the drainage network density is accurately represented in the HAND model, its representation of local soil draining potential is replicable for any type of terrain for which there is digital elevation data, irrespective of geology, geomorphology or soil complexities.

Furthermore, the HAND model has the potential to become a good framework for the development of an objective, quantitative, systematic and universal way to classify and map terrain.

References

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