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Development of an automated GIS tool for reproducing the HAND terrain model

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A B S T R A C T

Height Above the Nearest Drainage (HAND), a state-of-the-art topo-hydrological index, has been increasingly used in geo-environmental studies. It describes the local normalized drainage potential of a large region. To date, a trial and error and cumbersome multistep process has been used to obtain the HAND index which does not result in an optimal threshold for contributing area. This study aims at developing a user-friendly geographic information system (GIS) tool, HANDTool, using the Python programming language. We successfully applied the tool for the Chehel-Chai watershed, Iran and the random forest algorithm was used to model groundwater potential. Results revealed that the HAND index made a great contribution to groundwater potential modeling among the other conditioning factors. This tool gives valuable insights on the soil-topography-moisture shared interactions and vegetation condition, especially in ungauged watersheds.

Software and data availability

Name of tool HANDTool
Developers Samadi M., Kornejady A., and Rahmati O
Hardware required General-purpose computer (3 Gb RAM)
Software required ArcGIS 10.2
Programming languages Python© 2.7
Program size 231 KB
Availability and cost Freely available in GitHub (https://github.com/mahmoodsamadi/HANDTool.git)
Year first available 2018

1. Introduction

Topographical, hydrological, and topo–hydrological factors are useful in many fields of geo-environmental research including geomorphology, ecology, and water resources management. Since terrain attributes have long been known to correlate with soil properties (Gessler et al., 2000; Daws et al., 2002; Hansen et al., 2009), they provide important information about subsurface runoff dynamics and spatial patterns of soil moisture—key parameter in conditioning landscape ecology (Turner, 1989; Qiu et al., 2001; Dahl et al., 2007). Therefore, they can help in understanding hydrological processes and characterizing the properties of watersheds that depict suitability of a region for agriculture, reforestation or urbanization (Antrop, 2000, 2004; Rodriguez-Iturbe, 2000; Luck and Wu, 2002; Serra et al., 2008).

A range of topographic factors in terrain modeling are available, which allow several quantitative relief features and analytical interpretations to be obtained from the digital elevation model (DEM). Altitude, slope, aspect, drainage density and specific catchment area are common topographical descriptors in hydrology, geomorphology, and landscape analyses. In addition, relief shape factors such as curvatures (e.g. plan, profile, and general) and form indicators can also be produced based on a DEM. Furthermore, hydrological indices extracted from the DEM such as accumulated contributing area, stream density, superficial runoff trajectories, stream order, stream flow periodicity and groundwater related

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factors (e.g. Tarboton and Ames, 2001; Tarboton, 2003) have been applied in terrain modeling at the watershed scale (Gichamo et al., 2012). Although altitude (i.e. absolute height) has been used as a relief descriptor at large scales, its descriptive power may be limited when local environments in the fine scale relief are considered (Rennó et al., 2008).

The basic hypothesis in delineating drainage networks for deriving an apt topo-hydrological descriptor is the determination of channel heads, where concentrated fluxes begins to dominate over diffusive fluxes and where there is a transition from convex to concave profiles (O'Callaghan and Mark, 1984; Tarboton et al., 1991, 1992; Tarboton, 2003; Marthews et al., 2015). Hence, a number of studies applied automated or manual procedures for extracting DEM-derived stream networks through the selection of the contributing area threshold (CAT) (e.g. Tesfa et al., 2011; Gichamo et al., 2012; Bhowmik et al., 2015).

Several topo—hydrological factors have been proposed in previous years which allow us to describe, understand and predict soil—water gravitational potential energy, and water storage and movements (Seibert and McGlynn, 2007; Wu et al., 2008; Temimi et al., 2010). For example, the topographical wetness index (TWI) (Beven and Kirkby, 1979) has been widely applied to different fields for describing hydrological behavior and soil water/wetness conditions at the catchment scale (e.g. Sørensen et al., 2005; Sørensen and Seibert, 2007; Grabs et al., 2009; Pei et al., 2010; Besnard et al., 2013). However, the major limitation of TWI is it relies on some assumptions which are not necessarily true for all cases: i) it is assumed that groundwater gradients always equal surface gradients; and ii) it is also assumed that local slope is an adequate proxy for the effective downslope hydraulic gradient which is problematic in low relief terrain (Grabs et al., 2009; Lei et al., 2016). Therefore, this index is less suitable in flat areas because of rather undefined flow directions which can be significantly different from ground surface slopes and also more likely to change over time.

A new terrain model named Height Above the Nearest Drainage (HAND) has been introduced by Nobre et al. (2011), defined as *"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"*. Among the many terrain indices developed, the HAND is considered the best indicator of stationary soil moisture distribution because of its capacity to predict hydrological conditions of the terrain and soil environments has been successfully investigated (Sutanudjaja et al., 2013; Nobre et al., 2016). The rapidly growing application of HAND already includes hydrological modeling (e.g. Nobre et al., 2011; Cuartas et al., 2012), hydrological/geomorphological landscape analysis (e.g. Gharari et al., 2011; Nobre et al., 2016; Papageorgaki and Nalbantis, 2016; Owusu et al., 2017), landslide and/or flood susceptibility (e.g. Young and Nobre, 2012; Rosim et al., 2014; Martinis et al., 2015; Schlaffer et al., 2015; Bhatt et al., 2016; Policelli et al., 2016; Twele et al., 2016; Clement et al., 2017; Kesler, 2017; Kornejady et al., 2017a, 2017b; Manavalan, 2017; Sharma et al., 2017; Souffront Alcantara et al., 2017; Speckhann et al., 2017; Vimal et al., 2017), digital soil mapping (Zeng et al., 2016), surface water mapping (Huang et al., 2017), and riparian and plant ecology (e.g. de Freitas et al., 2014; Figueiredo et al., 2014; Moser et al., 2014; Schietti et al., 2014; Guitet et al., 2015).

The HAND model is a version of a Digital Elevation Model, where heights have been normalized according to the vertical distance to the nearest drainage channel (Nobre et al., 2011). For producing the HAND terrain model, a channel initiation must be recognized which is established by a contributing area threshold (CAT).

Predicting and understanding soil moisture conditions, subsurface runoff generation mechanisms, groundwater potential, and subsurface flow-related processes using topo-hydrological metrics is highly important, especially in developing countries where observed data from groundwater monitoring wells and detailed hydrological information are scarce. The development of automated GIS tools have been suggested to improve reliability and reproducibility in environmental modeling and geospatial research (Jolma et al., 2008; Steiniger and Hay, 2009; Neteler et al., 2012). This study is aimed at developing an effective tool for automatic computation of the HAND based on DEM data. Chehel-Chai watershed in Golestan province, northwest Iran, was selected as a case study for the purpose of this research due to its similarities in landform variety with central Amazonia where the HAND was first introduced. The specific objectives of this study are to (i) develop a novel and user-friendly geographic information tool using Python language, allowing the user to quickly generate a HAND layer; and (ii) compare contribution of the HAND to groundwater potential modeling along with other topographical/topo-hydrological factors using Random Forest model as a common and advanced machine learning algorithm.

2. HAND theory and tool development

A detailed description regarding the HAND index was presented in Rennó et al. (2008). Nobre et al. (2011) introduced the HAND index and its physical and hydrological basis, and Cuartas et al. (2012) made the first application of the HAND index in the parameterization of a distributed hydrological model. HAND normalizes the altitude of a basin based on the relative height along the drainage network and determines the gravitational or the relative drainage potential of an area. HAND is a relative height difference between a particular cell on a DEM map and its hydrologically related cell in the drainage channel. The resulting values can be interpreted as a normalized altitude map in which areas with low HAND values can exhibit saturation excess flow (saturate response zone). Moving on the terrain towards higher HAND values, different mechanisms prevail such as subsurface rapid flow (slope zone) and deep percolation flow (plateau zone). So, the HAND normalized topology is now a DEM enriched with useful information including response zones with specific runoff generation mechanisms, soil properties, and vegetation types.

The HANDTool was written in Python, a modern high-level programming language. Python is a general-purpose language, freely available and quite popular in the programming community. It allows development from scratch and/or the assemblage and connection of existing software components in a productive environment (Neuwirth et al., 2015; Wohlstadter et al., 2016). Karssenberg et al. (2007) attribute Python popularity to the fact that users do not have to be specialist in computer programing. The HANDTool appears in the ArcToolbox and runs as an extension of ArcGIS10.2 software.

The design of the HANDTool was divided into three parts: (1) input DEM and topo-hydrological computations, which contains all the code that introduces the DEM (in raster format) and the correct identification of the stream network, and (2) selection of the method for determining CAT, which contains codes for manual and automatic procedures, and (3) output, which contains codes that generate the HAND layer (in raster format) along with other supplementary layers such as corrected DEM, flow direction, flow accumulation, watersheds, and automatically extracted stream network (if needed). The graphical user interface is highly important in model designing, which allows users to change important parameters as well as to select the calculation procedures based on the available data and maps. The conceptual architecture of HANDTool is illustrated in Fig. 1.