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ESSAY

Towards improved global estimates and model representations of water storage in the unsaturated zone

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Abstract

The unsaturated zone is a globally important, dynamic water store, which affects water resources, agriculture and pollutant transport. Despite this, the magnitude of unsaturated zone water storage remains highly uncertain. This work provides the first global estimates of the magnitude of this store (1.0×10^5 km^3) in comparison to recent estimates of global modern groundwater (3.5×10^5 km^3), before presenting a roadmap for improved representation of the unsaturated zone in global hydrological models.

Keywords Unsaturated zone · Rock moisture · Global hydrological model

Introduction

Water stored in the unsaturated zone has been shown to influence pollutant transport, storage and fate (Koroša et al. 2020), surface vegetation (Querejeta et al. 2007) and biogeochemical cycling (Kim et al. 2017). The magnitude of water storage in the unsaturated zone has been highlighted to be large and of regional importance. For example, Zhu et al. (2019) estimate a volume of water up to 3.1×10^{12} m^3 stored in the unsaturated zone of the Chinese Loess Plateau, which accounts for 42.1% of the water resources in this region. However, understanding the magnitude of water storage in the unsaturated zone at the global scale is currently very limited. Here, an overview is provided of the current state of the science related to unsaturated zone water storage at the global scale. A first estimate of the possible magnitude of the store is made and a roadmap to improve the representation of the unsaturated zone in global hydrological models (GHMs) is presented.

Monitoring and modelling unsaturated zone water storage at the global scale: a brief synopsis of the state of the science

Current understanding of water storage in the unsaturated zone at the global-scale is primarily based on soil moisture estimates from in situ measurements (Vereecken et al. 2008) and remote sensing (Vereecken et al. 2016; Peng et al. 2017). The development of a global-scale soil moisture monitoring network (Dorigo et al. 2011) has allowed large-scale evaluation of soil moisture data for incorporation into GHMs. However, a significant proportion of the globe has a depth to water table of over 10 m, with a modelled maximum depth to water of 236 m (Fan et al. 2013). In-situ and remotely sensed soil moisture data can only penetrate c. 1 m depth (Ahlmer et al. 2018), and consequently this leaves a large proportion of storage in unsaturated bedrock relatively unaccounted for (Dawson et al. 2020).

Very few studies have characterised moisture and storage in the deep unsaturated zone (taken here to be beneath the zero-flux plane, the depth below which water movement is downward) (Ireson et al. 2006; Zhu et al. 2019). Studies of the deeper unsaturated zone are principally carried out with the aim of quantifying recharge to the saturated zone (Wang et al. 2009; Mattern and Vanclooster 2010; Min et al. 2015; Xiang et al. 2019). Such studies have used tracer experiments (Li et al. 2017) and solute profiling (Huang et al. 2016) alongside other conventional recharge estimation

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techniques (Healy and Scanlon (2010)). The rate of recharge to groundwater has been estimated in global modelling by the rate of drainage through the soil zone (Lawrence et al. 2011; Min et al. 2015) with little or no consideration of the underlying bedrock geology, or depth to water table (Schlemmer et al. 2018). Whilst remote sensing and earth observation data (e.g. GRACE) have been used extensively to identify changes in groundwater storage at the global scale (e.g. Li et al. 2019), such data cannot differentiate between water storage in the saturated and unsaturated zone without additional secondary data (e.g estimation of saturated zone water storage from in-situ measurements, see for example Brookfield et al. (2018)).

Where in situ measurements are not practical, pedotransfer functions have been used to derive hydraulic properties of the unsaturated zone from surface soil textural classes (Tóth et al. 2015). However, these are often confined to the top few metres of the unsaturated zone (Riebe et al. 2017). Pedo-transfer functions based on soil textural classes cannot be extrapolated accurately through the unsaturated zone, due to differences in the hydraulic properties and flow mechanisms between the bedrock and overlying soils (Katsura et al. 2006). Rempe and Dietrich (2018) differentiate between soil water and water stored in fractured bedrock, describing water storage in the bedrock as ‘rock moisture’; they further highlight its importance and lack of definition and inclusion in GHMs. In the context of the global water budget, no estimate of the magnitude of global unsaturated zone water storage has been made to date.

A first estimate of the magnitude of unsaturated zone water storage at the global scale

Using a global map of depth to water table (Fan et al. 2013) and a global porosity dataset (Gleeson et al. 2014) at a 0.25-degree global resolution, the potential magnitude of water storage in the unsaturated zone globally is calculated. Assuming a global average water saturation of 25% +/- 10%, total global water storage in the unsaturated zone is estimated to be $1.0\ \mathrm{x}10^5\mathrm{km}^3$ +/- $4.0\ \mathrm{x}\ 10^4\mathrm{km}^3$. A best estimate of the modern groundwater volume in the saturated zone is $3.5\mathrm{x}10^5\mathrm{km}^3$ ($2.4\mathrm{x}10^5\mathrm{km}^3$ - $3.8\mathrm{x}10^6\mathrm{km}^3$ accounting for uncertainty in model permeability, Gleeson et al. (2016)), with the majority of this volume thought to be stored in the upper 150 m below the ground surface (Gleeson et al. 2016). This is the same order of magnitude as the first unsaturated zone water estimate above.

A roadmap to improving representation of the unsaturated zone in GHMs

Significant uncertainties in water saturation at depth means that the estimate of global unsaturated zone water storage made above can only be used for the purpose of highlighting the possible magnitude of the store. Given the potentially significant water storage volume and its implications for water supply to surface vegetation (Beyer et al. 2016), groundwater protection (Saâdi et al. 2018) and aquifer recharge (Mattern and Vanclooster 2010), improved representation of unsaturated zone water storage in GHMs is essential.

Figure 1 outlines a roadmap to achieve this. A significant challenge at present is the lack of standardised terminology across different research communities (soil scientists, hydrogeologists, global hydrological modellers, scientists working with remote sensing earth observation datasets, e.g. GRACE) related to the unsaturated zone, particularly the distinction between shallow soil moisture and deeper unsaturated water storage. Consequently, a concerted effort to build consensus across these research communities to agree common terminology and meaning (e.g. providing definitions of the “deep” unsaturated zone) as well as data and reporting standards for future work is required. This initial task in itself is a long term investment and could be achieved through a new commission of the International Association of Hydrogeologists (IAH) and a number of community workshops. Common data and reporting standards should build on existing work to develop data models for the geosciences (e.g the Open Geospatial Commission Geoscience Markup Language). Such agreed terminology and standards should be published for reference for future research. Subsequently, a collation and synthesis of data from existing peer-reviewed and grey literature should be undertaken. Although a considerable task, this could consist of extraction of data related to the unsaturated zone (e.g. unsaturated zone water content) and how this varies with depth, time and hydrogeological setting. Data mining techniques could be exploited to achieve this, and the resulting data should be made publicly available (including through dissemination through data-focussed journals) and evaluated to develop a conceptualisation of unsaturated zone water movement at the global scale as a function of the variables above. Both the collated data and conceptualisation would then be used to re-evaluate structure and parameterisation of unsaturated zone processes in GHMs. The differences in scale, measurement and modelling approaches between field studies and regional to global observational datasets and

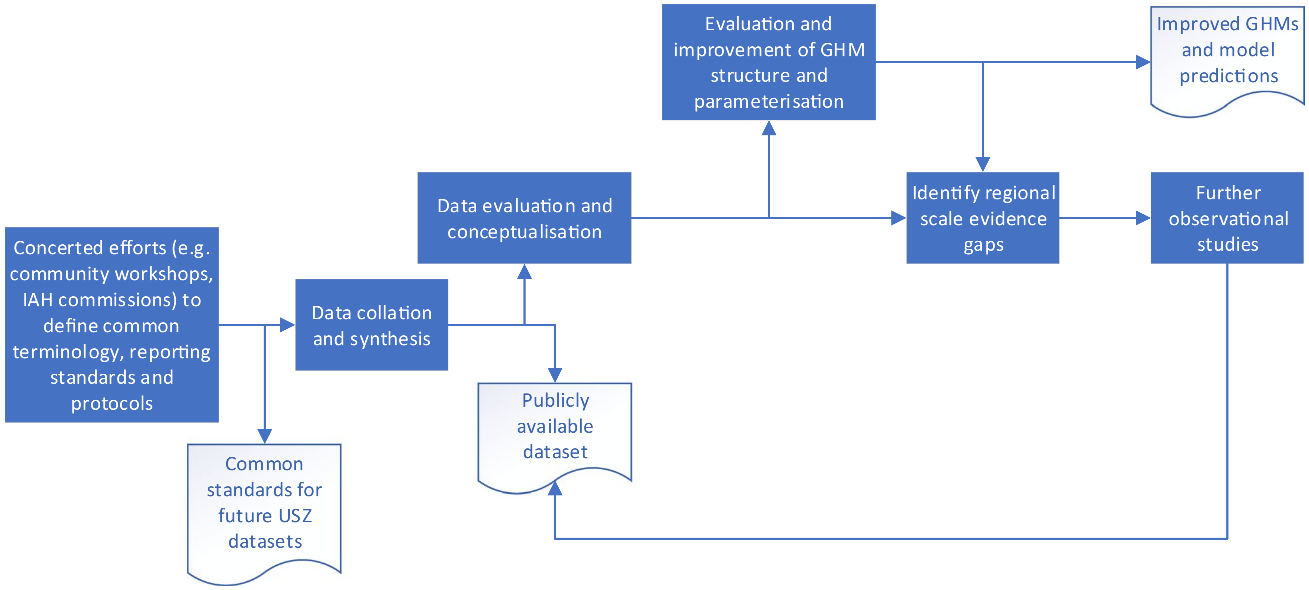

Fig. 1. A roadmap for improved representation of the unsaturated zone in GHMs. Filled boxes are activities and open boxes are outputs. USZ = unsaturated zone, GHM = global hydrological models, IAH = International Association of Hydrogeologists

models makes this challenging, and so the development and use of upscaling techniques should be central to this task. Where the data and conceptualisation show GHMs to have structural and parametric deficiencies (e.g. direct connection between the soil zone and saturated zone), further work could be undertaken to refine these GHMs. It is anticipated that such refined GHMs could (1) lead to improved predictions of the impacts of global change on the hydrological cycle and (2) help identify regional scale evidence gaps where further observational studies would be of benefit to better constrain the significance of unsaturated zone water storage.

The roadmap outlined here is intended to stimulate discussion amongst the hydrogeological research community as to how to engage with the soil science and global scale hydrological modelling communities to improve representation of the unsaturated zone in GHMs. The broad activities required are outlined above and in Fig. 1. However, this essay avoids being overly prescriptive on the required tasks, as such efforts need to be driven by the wider hydrogeological research community from the bottom-up. Whilst developed at the global scale, many of the principles (agreement of terminology, data synthesis and evaluation, existing model evaluation and refinement) of Fig. 1 also apply at the scale of large river basins, and could be adapted here accordingly.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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