1   # HESS Opinions: Are soils overrated in hydrology?

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12   ## Abstract

13   Traditional "physically-based" hydrological models are based on the assumption that soil is key in

14   determining water's fate. According to these models, soil properties determine water movement in

15   both saturated and unsaturated zones, described by matrix flow formulas known as the Darcy-

16   Richards equations. Soil properties would also determine plant available moisture and thereby

17   control transpiration. These models are data demanding, computationally intensive, parameter rich

18   and, as we shall show, founded on a wrong assumption. Instead, we argue the reverse: it is the

19   movement of the water through a porous medium, creating preferential patterns, that determines

20   soil properties; while water movement is primarily controlled by the ecosystem's reaction to the

21   climatic drivers. According to this assumption, soil properties are a "consequence", rather than a

22   "cause" of water movement. It is not the soil that is in control of hydrology, it is the ecosystem. An

23   important and favourable consequence of this climate and ecosystem-driven approach is that

24   models developed with this approach do not require soil information, are computationally cheap,

25   and parsimonious. Our assumption is motivated by several arguments. Firstly, in well-developed

26   soils the dominant flow mechanism is preferential, which is not particularly related to soil

27   properties, such as pF curves. Secondly, we observe that it is the ecosystem, rather than the soil,

28   that determines the land-surface water balance and hydrological processes. Top-down analysis by

29   large-sample datasets reveal that soil properties are often a poor predictor of hydrological

30   signatures. Bottom-up hydrological models usually do not directly use field measurements of the

31   soil, but "rebalance" the observed soil texture and translate it to soil structure by vegetation

32   indices. Thus, soil-based models may be appropriate at small spatio-temporal scale in non-

33   vegetated and agricultural environments, but introduce unnecessary complexity and sub-optimal

34   results in catchments with permanent vegetation. Progress in hydrology largely relies on

35   abandoning the compartmentalized approach, putting ecosystem at the centre of hydrology, and

36   moving to a landscape-based modelling approach. This change in perspective is needed to build

37   more realistic and simpler hydrological models that go beyond current stationarity assumptions,

38   but instead regard catchments as the result of ecosystems' coevolution with atmosphere, biosphere,

39   hydrosphere, pedosphere, and lithosphere.

40

1   Introduction

42   Soil is important. It forms the substrate of the terrestrial ecosystem and hence is a crucial element

43   of the critical zone of life on Earth (Banwart et al., 2017). Recently it has been demonstrated that

44   the soil forms an ecosystem in itself, full of micro-biotic and macrobiotic life (Ponge, 2015).

45   Fungi forming dense underground networks live in symbiosis with vegetation, exchanging

46   nutrients for carbon, which makes them responsible for the larger part of subterranean carbon

47   storage (Domeignoz-Horta et al., 2021). Soils are full of life. Above ground live cannot survive

48   without sub-surface life; they are both part of the same ecosystem. How this ecosystem functions,

49   evolves and survives depends on the climatic and geological boundary conditions. Through

50   evolution and natural selection, the ecosystem has found ways to make best use of the climatic and

51   geological resources. In doing so, it manipulates the substrate on which it grows. It manipulates

52   key hydrological characteristics such as: interception capacity, infiltration capacity, moisture

53   storage capacity, preferential pathways to replenish moisture stocks and recharge, and subsurface

54   drainage. So, soil is regarded as the key to hydrological processes (Lin et al., 2006). Yet, in (most

55   established) hydrological models, soils are simplified to soil classifications (Freeze and Harlan,

56   1969; Refsgaard et al., 2022), such as sandy, clayey, or loamy soils with their related soil

57   characteristics, such as porosity, moisture retention capacity, wilting point, plant available

58   moisture, etc., which are subsequently combined by the rooting depth of the dominant vegetation

59   (e.g. Drewniak, 2019, Lu et al., 2019). But this is the wrong way round.

60   Traditionally, hydrologists assume that the root zone storage is a function of plant available

61   moisture and rooting depth (Yang et al., 2016). This approach considers plant available moisture

62   and rooting depth as the independent variables, and root zone storage as the dependent variable.

63   But it is the opposite. Plant available moisture and rooting depth are a function of root zone

64   storage, given some environmental constraints such as soil type and soil depth. Obtaining the

65   detailed spatio-temporal root and soil information at a global scale is virtually impossible (Or,

66   2019), but fortunately not necessary.

67   It is not the soil that determines the hydrology, it is the interaction between ecosystem and climate.

68   The climate provides the driver to the survival strategy of the vegetation. As a result, the

69   vegetation develops a rooting strategy, which results in a certain moisture buffering capacity (Gao

70   et al., 2014; Wang-Erlandsson et al., 2016). Depending on the soil, this buffer translates in a root

71   depth, extent, density and possibly access to deeper groundwater (McCormick et al., 2021). So, for

72   hydrological modelling it is not useful to measure soil characteristics and rooting depth. We do not

73   need to know these dependent variables if we can determine root zone storage directly.

2   The soil-centred hydrological perspective

75   It is a deeply rooted perception in hydrology that soil is key in controlling rainfall-runoff

76   processes (Vereecken et al., 2022). Over a century ago, soil physicists developed the laboratory-

77   scale matrix flow theory, which is still widely used in so-called "physically-based" hydrological

78   and land surface models (LSMs) (Brutsaert et al., 2015; Xie et al., 2020). This theory describes

79   flow in porous media based on equations that depend on soil hydraulic properties (e.g. porosity,

80   hydraulic conductivity), which are typically associated to soil texture classes (e.g. clay, loam,

81   sand). Darcy's law describes matrix flow under saturated conditions through a porous medium

82   under a head gradient. Richards' equation regards matrix flow under unsaturated conditions in the

83   vadose zone, determining water flow direction and velocity. The matrix flow in most cases is

84   regarded as a well-established theory, much like classical mechanics. To simulate catchment

85   hydrology, matrix flow equations have been extended to distributed physically-based models,

86   cutting catchments into rectangles or triangle fragments, and using topography to drive soil water

87   movement vertically and laterally (Duffy, 1998; Refsgaard et al., 2022). The water infiltration and

88   vertical redistribution in most land surface models are also based on simplified Richards

89   equations, for example in diffusivity form (Vereecken et al., 2019). These models generally

90   require many space and soil-dependent parameters that require substantial calibration and

91   generally lead to equifinality.

92   However, by tracer field experiments, such as dye and isotope studies, matrix flow has been

93   scarcely observed, simply because a well-prepared homogenous soil under lab conditions does not

94   exist in nature. Most soils contain crevices, preferential channels, and openings that transmit free

95   water quite rapidly to the sub-surface, which is termed as preferential flow (Beven and Germann,

96   1982; McDonnell et al., 2007; Beven, 2018; Zehe et al., 2021).

97   To allow for preferential flows, modelers proposed more complicated models, which involved

98   even more free parameters to fit with observations. Unlike matrix flow, which has clear

99   description of water movement in homogenous porous media, it is much more challenging to

100   describe preferential flow by succinct mathematic equations. Although there have been dual-

101   continuum, dual-porosity, or dual-permeability modifications (Jarvis et al., 2016), most models are

102   still based on matrix flow theory (Weiler, 2017). Because of the extreme complexity of soil

103   preferential flow in nature, it is extremely hard, if not impossible, to develop an accurate model to

104   describe and predict even microscale water movement, the challenge is exponentially greater

105   when we upscale preferential flow from spot-scale to hillslope or catchment scales (Davies et al.,

106   2013; Germann, 2014; Or, 2019). However, this increase of model complexity, with more free

107   parameters to calibrate, did not show a clear improvement in the simulation of soil moisture,

108   groundwater head, and discharge (Glaser et al., 2019).

109   From the beginning, preferential flow theory was regarded as the main culprit challenging the

110   foundation of physically-based hydrological models, but it did not help the model builder. The

111   focus on preferential flow appeared not to shed light on a solution, but rather made the fog even

112   denser.

113   Both matrix flow and preferential flow models are based on the *a priori* assumption that: soil

114   properties are key in describing hydrological processes. In this study, we question the general

115   validity of this assumption, and ask whether thinking outside of the box of the soil-based

116   modelling framework could promote alternative, perhaps simpler theories, that help explain the

117   observed patterns of hydrological variability.

3   Does soil variability matter in catchment hydrology?

3.1   Does soil influence the long-term water budget

120   Globally, based on ERA-5 data (the fifth generation of ECMWF atmospheric reanalysis), annual

121   average terrestrial precipitation (P) is 745 mm/yr (111 km^3/yr), of which 440 mm/yr (65.5 km^3/yr,

122   60% of P) returns to the atmosphere as evaporation (E), and 305 mm/yr (45.5 km3/yr, 40% of P)

123   generates runoff (Q) (Figure 1). It is clear that evaporation rather than runoff is the dominant flux

124   after precipitation.

125   For terrestrial evaporation, the total global land area is 145 million km^2, of which 104 million km^2

126   (72%) is vegetated. Of total evaporation (E_{total}), soil evaporation only happens in the topsoil, with

127   a limited amount, only 6% of E_{total} (Good et al., 2015). As evaporation from vegetation and ground

128   interception accounts for 27%, transpiration is the largest flux at about 60-70% of E_{total} (Coenders-

129   Gerrits et al., 2014; Lian et al., 2018). An increasing number of studies confirmed that landuse

130   change, e.g. deforestation and afforestation, significantly alter runoff generation (Fenicia et al.,

131   2009; Nijzink et al., 2016; Sun et al., 2020). Thus, vegetation, and more correctly the ecosystem,

132   rather than soil, is the determining factor of the global and catchment water balance.

3.2   Do soil-centred models reproduce observed patterns of
hydrological variability?

135   In reductionist thinking the lead paradigm is that "the whole is the sum of the parts" (Sivapalan et

136   al., 2003). Bottom-up models are developed on the basis of small laboratory-scale laws, where the

137   assumption is that microscale laws remain valid after upscaling. Due to the difficult-to-measure

138   soil hydraulic properties (SHPs), such as the water retention characteristics, unsaturated and

139   saturated hydraulic conductivity, modelers have used soil pedotransfer functions (PTFs) to

140   correlate readily available soil properties, such as soil texture (i.e. sand-, silt-, clay- content),

141   organic matter, and bulk density with SHPs (van Looy et al., 2017; Or, 2019).

142   There are several critical issues with this approach, which result in inevitable biases: 1) most soil

143   property parameters are measured by pedologic surveys, at great expense and efforts (Van Looy et

144   al., 2017). Due to limited field measurement, most soil property maps rely on uncertain

145   interpolations and upscaling, which are based on soil-forming factors such as climate, parent

146   material, topography, biota, and time (van Looy, 2017); 2) PTFs are usually obtained by using

147   measurements from uniform soil samples, and performed in laboratory-scale experiments, which

148   merely reflect disturbed and therefore unnatural conditions; 3) the parameters obtained at the

149   laboratory scale are not necessarily the same at the modelled scale, which requires upscaling

150   assumptions, which are difficult to verify, or recalibration, which is hampered by equifinality; 4)

151   as emerging properties are scale-dependent, the processes that are important at lab or plot scale are

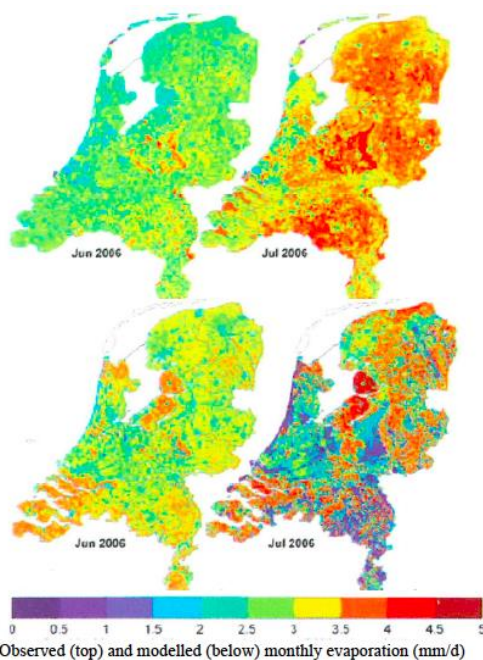152   not necessarily important at catchment scale (Blöschl and Sivapalan, 1995).

153   Figure 1. is a nice illustration of how a "physically based" model, making use of detailed soil

154   information, can make completely wrong predictions under extreme circumstances (Beekman et

155   al., 2014). On average, these models may function adequately, as almost all hydrological models

156   do under average conditions, but the example of Figure 1. shows how during a relatively extreme

157   drought in The Netherlands the modelled evaporation diverts considerably from observations.

158   The observed evaporation was obtained by interpolation of eddy-covariance and lysimeter

159   observations using ETLook, an energy balance-based evaporation product (Bastiaanssen et al.,

160   2012). The modelled evaporation was generated by the dominant Dutch hydrological model (NHI)

161   which heavily relies on detailed soil maps and soil observations. The June 2006 picture in the

162   lower part, in fact, mimics the soil map. Red (high evaporation) is seen on clay soils and purple

163   (almost no evaporation) on sand. It is funny to see that in reality (top right) the forested sandy part

164   at the centre of The Netherlands was evaporating lushly, whereas in the model (bottom right), this

165   ecosystem appeared to be dead. In fact, all ecosystems continued to evaporate well during this dry

166   month. Apparently, the ecosystems had prepared for this eventuality and had created enough root

167   zone buffer to overcome this period of drought.

168   Although such mismatch between distributed model outputs and observed patterns are not

169   infrequent, they are typically not regarded as a challenge to the basic model assumptions, but

170   rather, as a problem associated to the uncertainty in model inputs. Hence, such soil-centred

171   hydrological models remain vivid under the hope that "novel, highly resolved soil information at

172   higher resolutions than the grid scale of LSMs may help in better quantifying sub-grid variability

173   of key infiltration parameters" (Vereecken et al., 2022).

174   Observed (top) and modelled (below) monthly evaporation (mm/d)

175   Figure 1. Evaporation during June (left) and July (right) of 2006 in The Netherlands. Modelled

176   below and observed on top (from Beekman et al., 2014)

177   **3.3   Is soil a good predictor for hydrological signatures?**

178   The top-down approach, as a genuine way of learning from data, is amenable to systematic

179   learning and hypothesis testing (Sivapalan et al., 2003), which is more suitable to understand the
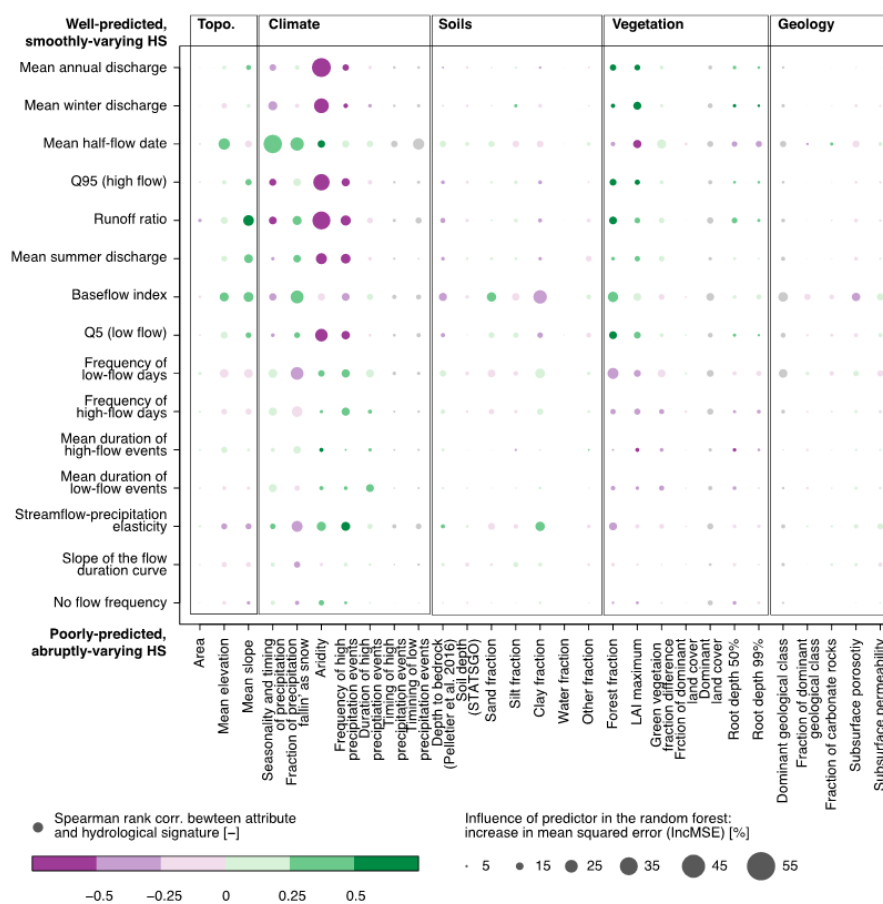
180 complex hydrological system. There are many predictors for hydrological signatures, including

181 climate, vegetation, topography, geology and soil. Interestingly, in catchment hydrology, soil

182 properties are often a poor predictor of hydrological signatures. Addor et al., (2018) used 671

183 catchments in the USA and found that, compared to soil, landscape features, i.e. vegetation and

184 topography, have stronger correlations with hydrologic signatures, not only for mean runoff, but

185 also for high-flow, low-flow, and runoff seasonality (Figure 2).

186 The soil may be important for small scale (agricultural) hydrology, but this importance is easily

187 overridden by other factors at larger scale, for example climate, topography, vegetation, and

188 geology. All these factors are intertwined, and result in preferential flow not only in the soil

189 profile, but for all hydrological processes at multi-scales (Uhlenbrook, 2006), ranging from

190 fingering, macropores, forest canopy, leaves, roots, fractures, rills and gullies, all the way to the

191 river network, and even in the groundwater system (Savenije, 2018). These preferential flow

192 patterns have great influence on all hydrological processes, including infiltration, percolation,

193 groundwater discharge, and river channel routing (Rodrigues-Iturbe and Rinaldo, 1997; Sivapalan,

194 2006; Savenije and Hrachowitz, 2017). The infiltration capacity, in the absence of vegetation, may

195 be a determining factor for infiltration excess overland runoff (Hortonian flow), but this scarcely

196 occurs in natural vegetated landscapes where the ecosystem facilitates infiltration, even in arid

197 regions (Zhao et al., 2019). In mature ecosystems, runoff is dominated by subsurface flow, which

198 is a storage-discharge relationship. The preferential flow path, as the connector between small-

199 and large-scale observations, makes the surface, rootzone and ground water systems react to

200 rainfall as an integrated fill-and-spill system (Tromp-van Meerveld and McDonnell, 2006). This

201 allows modellers to merely focus on input-output and storage change, to reproduce the complex

202 rainfall-runoff processes through the heterogeneous but fractal patterned surface and subsurface.

203 Interestingly, in practice, simple catchment hydrological models, even without explicitly

204 considering detailed matrix flow or preferential flow, can reproduce complex rainfall-runoff

205 processes, with surprisingly good performance. The reliability and robustness of the widely used

206 HBV (Seibert, 2018), GR4J (Perrin et al., 2001), Xinanjiang (Zhao, 1992), and FLEX (Fenicia et

207 al., 2011; Gao et al., 2022), have been tested and validated in a wide range of regional and global

208   hydrological studies (Bergström and Lindström, 2015; Mao and Liu, 2019; Wang et al., 2021).

209   There are also examples of distributed models that describe the observed variability of

210   hydrological signatures without relying on soil information (e.g. Boer-Euser et al., 2016; Fenicia

211   et al., 2016; Gao et al., 2019; Dal Molin et al., 2020; Fenicia et al., 2022).

212

Figure 2. Comparison of the influence of catchments attributes and hydrological signatures for 671
U.S. watersheds (from Addor et al., 2018). Large, brightly coloured circles imply strong
correlations and high influence. (Reprinted by permission of John Wiley and Sons).

4   Putting the ecosystem at the centre of hydrology

4.1   The ecosystem is the ultimate water manager

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217

218   Engineering hydrologists have a long tradition to focus on runoff generation, which represents at

219   the same time the most valuable water resources and the cause of water related disasters, i.e.

220   floods and droughts. There is limited realisation that runoff is merely the ecosystem's by-product

221   of water use (Bonan, 2015), only accounting for 40% of the precipitation, while the ecosystem

222   evaporates 60% of precipitation back to the atmosphere in its drive to grow and survive.

223   A natural ecosystem can only survive if it organizes its resilience. This resilience requires not only

224   sufficient moisture storage in the root zone, to overcome critical dry spells, but also sufficient

225   infiltration capacity and subsurface drainage to maintain moisture levels between acceptable

226   boundaries: not too wet and not too dry. If given sufficient time, the ecosystem will improve the

227   infiltration capacity both to replenish water in the root zone and to prevent runoff; seldom do we

228   observe surface runoff in a natural environment. The ecosystem creates preferential flow paths

229   that facilitate infiltration in order to retain nutrients and soil particles and to direct rainfall to

230   where it is most needed. If there is too much infiltration, then sub-surface drainage by preferential

231   recharge and sub-surface drainage patterns on hillslopes evacuates excess water. Preferential flow

232   rapidly delivers the excess water, bypassing the rootzone, to the groundwater system (McDonnell,

233   2014). By wave propagation the groundwater head created by the recharge pushes pre-event

234   groundwater to the streams (Kirchner et al., 2003; Hrachowitz et al., 2016; Worthington, 2019)

235   also through preferential flow patterns (Savenije, 2018). In summary, prevailing preferential flow

236   paths, mostly as a result of a variety of biological activities, determine rainfall partitioning and

237   runoff generation, moving beyond plot-scale heterogeneity and process complexity, where

238   landscape and ecosystem are the determining factors rather than the soil.

239   Modelers utilizing a bottom-up approach also noticed that the simple paradigm of using soil

240   texture as a main predictor of SHPs is problematic (Bonetti et al., 2021). Gutmann and Small

241   (2007) have shown that soil textural classes, across a range of climates and vegetation covers,

242   merely explained 5% of the variance obtained from the real SHPs. It was found that 95% of the

243   default soil parameters in a state-of-the-art landsurface model were significantly different from

244   region-specific observations (Kishné et al., 2017).

245   With the biased observation and the scale effect, modelers need to recalibrate numerous free

246   parameters. There are studies that "rebalance" the soil texture information and highlight the

247   importance of soil structure, originated by soil biophysical activity (Or, 2019; Fatichi et al., 2020).

248   These models do not directly use field measurements of the soil, but "rebalance" the observed soil

249   texture and translate it to soil structure by vegetation indices, e.g. the aboveground vegetation

250   biomass and leaf area index (LAI) (Bonetti et al., 2021). Involving vegetation cover and

251   productivity prominently improved the hydrologic response with respect to runoff generation,

252   infiltration and drainage (Or, 2019). Not only the physically-based models, but also the empirical

253   soil-based models, for example the soil conservation service (SCS) method in SWAT model (soil

254   water assessment tool), also involve landuse data to "rebalance" the soil-based curve number in

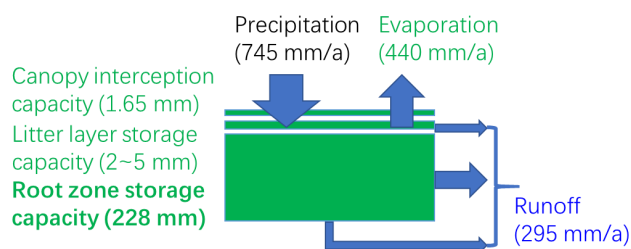255   catchment simulation (Arnold et al., 2012).

4.2   The rootzone is the key element in hydrology not the soil

257   Vegetation as a living organism optimizes its rootzone water storage to stabilize water supply at

258   minimal carbon cost, and sometimes access to the deeper groundwater, to cater for periods of

259   drought (Gao et al., 2014; McCormick et al., 2021). From a hydrology perspective, the vertical

260   profile of the critical zone can be divided into different layers, i.e.: canopy, litter layer, root zone,

261   water transition zone, unconfined groundwater, and confined groundwater. The most active layers

262   in the critical zone defining rainfall partitioning and related hydrological processes include: the

263   canopy, litter layer, and root zone. Globally, the vegetation interception storage capacity of

264   terrestrial ecosystems is about 1-2 mm, estimated by remotes sensing LAI data (De Roo et al.,

265   1996). The litter layer storage capacity differs in different ecosystems, but it is likely to increase

266   the total interception storage capacity to around 2-5 mm (Shi et al., 2004). For determining the

267   rootzone storage capacity of ecosystems, the mass curve technique appeared to work well locally

268   and globally (Gao et al., 2014; Wang-Erlandsson et al., 2016) whereby use was made of ERA-5

269   evaporation data to estimate, resulting in a global average root zone storage capacity of 228 mm

270   (Figure 3). Hence, rootzone storage capacity is significantly larger than interception and litter

271   layer water storage capacities. Beneath the rootzone, water in the transition zone between root

272   zone and groundwater and the unconfined groundwater does not have phase changes, and will be

273   discharged as runoff under natural condition. The deep confined groundwater has a very long

274   transit time, without much connection to surface processes, and is not considered in surface runoff

275   calculation in most cases. Hence, the root zone storage plays the dominant role in catchment

276   hydrology, determining how catchments respond to rainfall.

277   It is worthwhile noting that rootzone and soil have a strong connection, but are essentially

278   different things. The soil profile can reach over hundreds of meters' depth, e.g. the Loess Plateau

279   in China (Zhang et al., 2014), of which only the rootzone is the active area, whereby the soil is

280   merely the substrate of it. Rootzone storage can also be larger than soil water storage, for example

281   in karst mountainous areas where soil is thin and discontinuous, bedrock storage serves as an

282   important source of plant-available water (McCormick et al., 2021). Rootzone water storage is a

283   more accurate term in hydrology, which cannot be measured directly, but with clear physical

284   meaning, similar to the runoff depth and runoff efficiency.

286   Figure 3. The importance of root zone storage capacity in catchment hydrology. All the numbers

287   are global average values in vegetated area, obtained by ERA-5 data from 1980 to 2020.

4.3   Landscape-based model: the giant view of hydrology

289   A soil-based model is like an ant's perspective, observing a complex world of heterogeneities and

290   randomness. Landscape, as the integration of topography and landcover, being the long-term co-

291   evolution of ecosystem, atmosphere, lithosphere, pedosphere, hydrosphere, and human activities

292   (Mücher et al., 2010; Wu, 2013; Troch et al., 2015) is rather the giant's perspective (Savenije,

293   2010). The pattern of hillslope, landscape and catchment only becomes visible when we zoom out

294   well beyond the microscale of the soil or the human scale, for that matter.

295   At landscape scale, hydrological laws can be simple: the fill and spill bucket model with

296   thresholds and associated time scales and the linear reservoir for groundwater are physically-

297   sound at hillslope and catchment scale (Savenije, 2010; Fenicia et al., 2011; Savenije and

298   Hrachowitz, 2017). Landscape-based models also use conservation of mass and energy, but

299   momentum transfer is made of conceptual relations that relate discharge to storage using

300   landscape and ecosystem characteristics, such as travel times and a probability function for runoff

301   thresholds. Geology as the substrates of hydrological processes also plays an important role on

302   slow processes. Interestingly, the underground hydrogeology system seems also self-organized

303   and structured (Savenije, 2018). For example, the recession parameter k is around 43 days in

304   worldwide catchments regardless of their climate, topography, soil, and geology (Brutsaert and

305   Sugita, 2008). Discovering these properties and related signatures benefit our understanding and

306   prediction of the dynamic adaption of ecosystems to environmental change, and the subsequent

307   impacts on hydrology (Gharari et al., 2014).

308   Explosive growth of remote sensing technology and powerful geographic information system

309   (GIS) toolkits provide unprecedented opportunities, with a giant's view, to closely read landscapes

310   and monitor their hydrological components in high spatial and temporal resolutions (Duan et al.,

311   2021; Crow et al. 2022). Various measurement techniques, e.g. eddy covariance, make it possible

312   to quantify the mass and energy budget at landscape scale (Jung et al., 2020; Lan et al., 2021). The

313   GRACE satellite provides independent estimates of moisture storage on Earth (Famiglietti et al.,

314   2015; Dong et al., 2022). These datasets form crucial complementary information to constrain

315   landscape-based model parameters, validate the internal fluxes, and eventually give more

316   physically-based and reliable simulation (Winsemius et al., 2006; Nijzink et al., 2018; Gao et al.,

317   2020).

5   Why is the soil-based modelling tradition so rooted in hydrology?

320   Occam's razor tells us "Entities are not to be multiplied beyond necessity". This principle gives

321   precedence to simplicity: of two competing theories, the simpler explanation of an entity is to be

322   preferred. Therefore, if soil does not play a significant role neither in the water balance nor in

323   rainfall-runoff processes, and if disregarding soil does not significantly affect model performance,

324   there is sufficient and fair reason to exclude soil properties in hydrological modelling. But then:

325   why are soil-based models so rooted in hydrology?

5.1   Agricultural bias

327   Since hydrology was born from chapters of agricultural and hydraulics textbooks (Rodríguez-

328   Iturbe and Rinaldo, 2004), the misunderstanding that soils are the determining factor in hydrology

329   is probably caused by the "agricultural bias". In agriculture, the focus is on seasonal crops. A

330   seasonal crop has limited time to develop a root zone storage that can buffer for longer term

331   variability. At best, it can buffer for average dry spells that may occur within an average year. This

332   is why modern agriculture requires water management by the farmer to buffer for natural

333   fluctuations. In agriculture, ploughing destroys preferential infiltration and sub-surface drainage. It

334   also limits the root zone storage capacity to the relatively small soil layer above the plough pan. In

335   such cases it is indeed the moisture holding capacity of the soil that determines the root zone

336   storage capacity.

337   As regards evaporation, it occurs in many ways: by transpiration, direct evaporation from leaf and

338   ground interception, bare soil evaporation, open water evaporation, sublimation, and in general

339   from all phase changes where liquid or solid water turns into vapour. All these mechanisms obey

340   different constraints and need to be modelled separately to arrive at a correct representation of

341   total evaporation. In that respect, the dominant widely used Penman-Monteith equation, so

342   successful in agriculture, is likely not appropriate to describe land-atmosphere interaction.

343   Unfortunately, this "agricultural bias" has been dominant in most hydrological work. We argue

344   that this deeply rooted soil-based perception may limit or even mislead the further development of

345   hydrological science, especially for next generation professionals.

5.2   Unreliable intuition

347   Hydrologists intuitively concern about soil. It could very well by the perspective of the ant that

348   causes it. As people, we are just too small to observe the larger scale processes that dominate

349   landscape hydrology. We tend to dig holes in the Earth and try to infer larger scale behaviour from

350 what we observe inside this hole. The human scale prevents us from seeing the larger picture. We

351 need the giant's perspective to recognise the patterns present in the landscape.

352 At the human scale, assuming that soil properties, such as texture and porosity, matter makes

353 intuitive sense. People tend to describe what they see (i.e. the consequence) rather than the cause,

354 and if they see water flowing or disappearing in the ground they think that it is because of such

355 soil properties. The role of the ecosystem as the driver is much more difficult to recognize,

356 because it is hidden to the eye. It requires seeing the environment as a living thing, which

357 continuously evolves and adjusts to changing circumstances. It also implies that the hydrological

358 properties are not constant over time. The root zone storage, the most critical control on rainfall-

359 runoff processes, is continuously changing in response to changing climatic and human drivers.

360 Instead of describing the 'now' as an invariant and static condition, with environmental properties

361 as a given, one has to think of the history that determined these environmental conditions, which

362 much more difficult to realise.

6 Conclusion

364 Hydrology is the blood stream of the ecosystem. Runoff is merely the excess water after

365 precipitation has replenished ecosystem's water deficit. Traditional "physically-based" models put

366 soil physical properties at the heart of hydrology which is misleading for both process

367 understanding and model development. In contrast we need an ecosystem-centred approach.

368 Nowadays there is much concern about the Critical Zone of the Earth, where virtually all life takes

369 place. The ecosystem is the ultimate manager of the critical zone, with hydrology as its blood

370 stream. We advocate a paradigm shift to put ecosystem and landscape at the heart of terrestrial

371 hydrology, and develop holistic and alive ecosystem-based hydrological models, with better

372 representation of hydrological processes in Earth system science.

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