Characteristics of soil and hillslope responses in humid tropical forests in Sumatra, Indonesia

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Abstract:

Extensive deforestation in tropical regions may significantly influence the hydrological cycle. However, subsurface runoff processes in thick soil layers in humid tropical forests are poorly understood; thus, the impact of land-use changes in such regions remains unclear. To understand runoff generation mechanisms in the humid tropics, we monitored groundwater and soil moisture dynamics in a forested hillslope in Sumatra, Indonesia. We also conducted field and laboratory experiments to determine soil hydraulic characteristics and used the results to simulate vertical infiltration and groundwater recharge. Although the soil is categorized as silty clay loam, the high infiltrability and high water retention capacity of the soil enabled infiltration during storm events and recharged groundwater. Within the 4–5 m thick soil layer at the foot of the hillslope, the shallow groundwater table quickly responded to rainfall and did not drop below a depth of 2–3 m, possibly due to continuous flow contributions from the upslope. Overall, this study demonstrates the importance of subsurface flow and vertical infiltration in thick soil layers in humid tropical regions.

KEYWORDS hillslope hydrology; subsurface flow; humid tropical forest; Sumatra; groundwater; infiltration

INTRODUCTION

In Southeast Asia, the rapid expansion of oil palm plantations and the associated deforestation are identified as important factors affecting the hydrological cycle. Within the 1975–2005 period, the forest-covered area in Indonesia decreased by 39 million hectares (Wicke et al., 2011). Specifically, in Sumatra, where 70% of the palm oil production in Indonesia comes from, the rate of deforestation is high (Wicke et al., 2011). Studies have reported many changes in the hydrological cycle in Sumatra, e.g. increasing flood frequency in the Batanghari river basin (Tarigan, 2016), lowering of well water levels during the dry season, and increasing fluctuation of streamflow during the wet season (Merten et al., 2016). Changes in groundwater levels also increase fire risk and carbon emission in the downstream peatland (Page et al., 2002). However, the effects of land-use change on the hydrological cycle are far from being fully assessed and understood due to limited understanding of runoff generation processes (Comte et al., 2012).

Runoff generation processes in humid tropical forests are distinct from those in temperate regions because of the different soil characteristics. Soils in humid tropical forests are usually rich in clay content, deeply weathered, and have a thickness of several meters (Verheye, 2009). In such soil layers, infiltration becomes a key determinant of runoff generation processes. Observations in the humid tropics have shown that a drastic decrease in hydrologic conductivity at a shallow depth impedes vertical infiltration and generates saturation overland flow during rainfall events (Bonell et al., 2010; Bonell and Gilmour, 1978). When this is the case, the contribution of vertical infiltration to groundwater would be small.

On the other hand, other studies demonstrated that vertical infiltration could prevail because of high soil hydraulic conductivity throughout the thick soil (Dykes and Thornes, 2000; Noguchi et al., 1997a; 1997b). This potential of vertical infiltration to significantly contribute to deeper subsurface flow in the thick tropical soil layer has been recognized but poorly studied due to the relative inaccessibility of study sites (Bonell et al., 1993; Bonell, 2009). Previous studies investigated the hillslope responses in thick tropical soil layers by measuring soil matric water potential, soil hydraulic properties, and streamflow responses (Dykes and Thornes, 2000; Noguchi et al., 1997a; 1997b). However, the groundwater responses in such thick soil layers have been poorly monitored, especially in humid tropical forest mountains. Investigating groundwater responses in the headwater of the Batanghari River in Sumatra, where a shallow groundwater table and thick soil layers characterize the watershed (Furukawa et al., 2005; Page et al., 2002), would provide essential insights for understanding the runoff generation processes in thick tropical soil layers.

This study aimed to investigate groundwater and soil moisture responses in the thick soil layer of tropical forests to storm events via field monitoring. We simulated the observed soil moisture responses using a one-dimensional...
finite-element unsaturated infiltration model to estimate groundwater recharge during the storm events. Based on the timing of the groundwater and soil moisture responses as well as the recharge amount, a conceptual model of subsurface flow processes in the thick soil layer was also presented.

METHODS

Site description

The study site is located in the headwater of the Batanghari River (basin area 42,690 km$^2$) in the Jambi Province, Sumatra, Indonesia (Figure 1). This study focused on a forested hillslope in Sekancing township, which is located on the west side of the river basin (2°15’26.4'' S, 102°10’20.7” E). A perennial stream flows at the bottom of the hillslope. The climate in Jambi Province is humid tropical with an average air temperature of 26.7 ± 0.2°C (mean ± standard deviation) and annual precipitation of 2,235 ± 381 mm as recorded between 1991 and 2011 (Drescher et al., 2016). This compared well with the observed annual precipitation (2,909 mm) in our study site during August 2017 to July 2018. Although the monthly precipitation rarely falls below 100 mm, there are two distinguished seasons: the wet season brought by the northwest monsoon from October to May (monthly precipitation 265 ± 90 mm during October 2017 to May 2018), and the dry season brought by the southeast monsoon from June to September (monthly precipitation 195 ± 44 mm during August to September 2017 and June to September 2018). The land-use is a secondary forest called ‘Jungle Rubber Agroforest’ (Joshi et al., 2002), where rubbers are sparsely planted in forest gaps without slash and burns. The primary forest is dipterocarps, and the understory is covered with vegetation (Figure S1).

The hillslope is characterized by a thick soil layer (Figure 1c). The hillslope stratigraphy was determined via dynamic cone penetration tests using a penetrometer with a weight of 5 kg and a fall distance of 50 cm (Figure 1d). This hillslope is 38 m long and 14 m high, and has a gradient that is approximately 20°. In the upper part of the hillslope, the soil layer is around 2 m thick, and towards its foot, the soil layer is up to 5–6 m thick. Based on our soil-particle analysis using sieve and hydrometer methods, the soil texture was found to be silty clay loam according to USDA definition. Below the soil layer is a weathered bedrock layer that consists of sedimentary rocks deposited during the Cenozoic era (Zhang et al., 2018). Following previous investigations, we defined the boundary between the surface soil and bedrock layer based on $N_c$ value of 50 (Katsura et al., 2014; Kosugi et al., 2006); $N_c$ values represent the number of hammerings required to penetrate 10 cm in the cone penetration test. During the well drilling at SK3, the weathered bedrock appeared at a depth of 150 cm, and we confirmed that the depth coincided with the point at which $N_c$ became greater than 50.

Field monitoring of hillslope groundwater and soil moisture

We monitored groundwater levels, volumetric soil moisture content, air temperature, and atmospheric pressure from April 26, 2018 to September 30, 2018. Ten-minute rainfall data were obtained using a tipping bucket rain gauge (Climatec, CPK-RAIN-1). Groundwater levels were measured at 10-minute intervals in three observation boreholes, named SK1 (571 cm in length), SK2 (616 cm), and SK3 (277 cm), installed along a transect (Figure 1d). The screens were opened from 1 m below the soil surface to the bottom approximately every 30 cm. The bottom of the observation well was uncovered and penetrated into the weathered bedrock. We used a monitor DAIKI, DIK-612A-B1 for gauging groundwater level in the boreholes, and a barometer DAIKI, DIK-615A-E1 for gauging atmospheric pressure and air temperature. The groundwater level sensors were calibrated based on the pressure and temperature

Figure 1. Maps of study sites: (a) Sumatra island, (b) Batanghari River basin, (c) Location of the studied forest hillslopes with 5 m elevation contour line, and (d) Cross-sectional views of the stratigraphy and location of the monitoring equipment. Data sources for (a), (b) and (c) are GADM (University of California, Berkeley, Museum of Vertebrate Zoology, 2015), HydroSHEDS (Lehner et al., 2008) and ASTER (Tachikawa et al., 2011), respectively.
data. Volumetric soil moisture content was measured at 10-minute intervals using dielectric soil-moisture meters installed at depths of 90 and 150 cm near borehole SK1 (UIZIN, SM150T). Dielectric soil moisture sensors were installed at the foot of the hillslope but not within the riparian zone so that the existence of both infiltration and subsurface flows could be examined. The calibration curve, i.e. the relationship between the dielectric permittivity and soil moisture, was derived from soil samples from 30 and 60 cm depths at the study site (Figure S2, Figure S3). According to the results, the saturated water content at 30–60 cm was between 62.3 and 66.1%. The difference in saturated water content between calibration samples (disturbed) and soil experiment samples (undisturbed) could be due to the extent of soil disturbance or sample variation.

We analyzed the event dynamics in the hillslope by dividing precipitation and groundwater records into multiple events. Following the rules adopted by Itokazu et al. (2013), a rainfall event was established if there was no rainfall for 12 h after the last precipitation. To understand the response mechanisms, we compared the rainfall, groundwater, and soil moisture response metrics corresponding to each event. The metrics, which are defined and summarized in Table SI, included total rainfall amount, antecedent rainfall amount, groundwater/soil moisture response timings and magnitudes.

RESULTS

Groundwater and soil moisture responses

The observation of the groundwater table at borehole SK1, which is installed at the foot of the hillslope (Figure 2a), showed the existence of shallow groundwater. Even during the mid-dry season (June to August 2018), the groundwater table at borehole SK1 was always maintained at 200–350 cm below the soil surface. This means that the steady groundwater table existed at depths of 100–250 cm

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Figure 2. (a) Observation record of hourly rainfall, groundwater depth from the ground surface, and volumetric water content. (b), (c), and (d) Fast and high-magnitude responses of the groundwater table at borehole SK1 during events #202, #158, and #179, respectively. Note that soil moisture observation at 150 cm (B150) showed a flat peak; this could be due to a measurement error, or the influence of the groundwater table. Therefore, to analyze response timing to rainfall in this study, only B90 data was used.
above the bedrock, given that the soil layer at borehole SK1 is approximately 450 cm thick as revealed by the results of cone penetration tests (Figure 1). Similarly, at borehole SK3, the stable groundwater table was at a depth of 150 cm in a 170 cm soil layer, suggesting that the groundwater table was maintained at 20 cm above the bedrock. The groundwater table at borehole SK2 was maintained at 300 cm below the surface early in the dry season (May) and dropped to approximately 350 cm in the latter part of the dry season (September). According to the stratigraphy shown in Figure 1, the groundwater table was at or slightly below the boundary between the soil and weathered bedrock layer.

Comparing rainfall and groundwater response features, we found that the shallow groundwater at borehole SK1 responded quickly with high magnitude to high-intensity rainfall events. In Figure 2a, the red arrows indicate the significant responses, and Table SII lists the response features. For example, during event #158 (Figure 2b), the groundwater table rose to 50 cm below the soil surface within 20 min after the peak rainfall and dropped to a depth of 200 cm within 24 h. We observed similar responses for events #179 and #202 (Figure 2c and d). Among all the 63 rainfall events monitored during the 5 months of observation, 19 events resulted in a response, either in boreholes or soil moisture, or both. Specifically, six out of the 19 events were high-intensity rainfall events, with a maximum rainfall intensity above 20 mm/h or antecedent rainfall above 30 mm. Figure 3 illustrates the box plots of the responses of the groundwater table at borehole SK1 during the high-intensity rainfall events and the other low-intensity rainfall events. For the six high-intensity rainfall events, the groundwater table at borehole SK1 responded within 44 min on average after the rainfall peak with a large response magnitude (170 cm on average), excluding the abnormally longer response time of event #220. This long response time corresponding to event #220 could be attributed to the lack of rainfall to overcome the large storage deficit. The initial groundwater depth was deep in #220 and #202, but the rainfall was less intensive compared with #202; under such conditions, it would take longer for the water level to rise. Compared with the low-intensity rainfall events, the response magnitude of the groundwater table was significantly larger during the high-intensity rainfall events based on a t-test with \( p = 0.02 \) (< 0.05). The response times of the groundwater table to rainfall were similarly short for both event groups with \( p = 0.40 \) (> 0.05).

The soil moisture responses at borehole SK1 suggested the recharge of vertical infiltration to the groundwater during high-intensity rainfall events. For the high-intensity rainfall events, soil moisture at depths of both 90 and 150 cm responded with high magnitudes (above 10%), and significant groundwater responses followed. During event #202 (Figure 2b), the response first occurred in the top layer (i.e. soil moisture at a depth of 90 cm), next in the middle layer (i.e. soil moisture at a depth of 150 cm), and then in the bottom layer (SK1 groundwater table). On the contrary, during events #158 and #179 (Figure 2c and d), the groundwater responded earlier than those of the soil moisture sensors in the surface and middle layers, and the response magnitudes of soil moisture were only 1–2% at a depth of 90 cm. Events #158 and #179 were less intense rainfall events compared with the other events, with an antecedent rainfall of 26.0 mm for event #158 and maximum rainfall intensity of 18.0 mm/h for event #179 (see Table SII). Considering borehole SK3, which was positioned at the upper hillslope, it was evident that the groundwater table responded quickly to the rainfall events, with an average response time of 33 min. This observation suggests a large contribution of vertical infiltration to the groundwater table at borehole SK3, possibly because the soil layer is relatively thin (approximately 170 cm). In this hillslope, therefore, both vertical and lateral subsurface flows should be understood in an integrated manner. However, given the limited availability of data and the computational difficulty of solving unsaturated and saturated subsurface flow in the thick soil layers, we primarily focused on the role of vertical infiltration in thick soil layers in the following subsection. The effect of lateral subsurface flow is discussed in the Discussion section.

**Vertical infiltration flow modeling**

The HYDRUS-1D model was used for the simulation of the observed soil moisture response of the hillslope (Text S1, Text S2, Table SIII). In the simulation, we aimed to replicate the observed variation of volumetric soil moisture at a depth of 90 cm below the soil surface close to borehole SK1. In this way, we examined the possibility of vertical infiltration as well as its contribution to the groundwater table in the thick soil layer. The soil moisture record at a depth of 150 cm was not suitable for model validation because it was often affected by the rise in the groundwater table, and HYDRUS-1D is not capable of simulating the interaction between the variable pressure-head bottom condition and the simulated seepage. Figure S4 shows the observed and simulated soil moisture at a depth of 90 cm during the seasonal transition from wet to dry season (from May 16, 2018 to June 7, 2018) and the dry season (June 8, 2018 to September 26, 2018) after a warming-up period of 10 days. The Nash-Sutcliff efficiency (NSE; Nash and...
Sutcliffe, 1970) and the percent bias were 0.58 and –0.14% for $\alpha_v = 0$ (1/cm), 0.50 and –0.27% for $\alpha_v = 1.0 \times 10^{-2}$ (1/cm), and 0.37 and 0.12% for $\alpha_v = 2.0 \times 10^{-2}$ (1/cm), respectively (Text S3) during the seasonal transition. These NSE values suggest ‘sufficient’ model fit (Moriasi et al., 2007) probably because the mismatch between the model and the observation made during low-intensity events lowered the NSE value. The high response magnitude and the short response time of the soil moisture during the high-intensity events, which were of interest to us, were replicated well in the model. During the seasonal transition period, soil moisture content after event recessions were maintained at the same level. After the onset of the dry season, the soil moisture level continuously dropped down during the no-rain period, which was not possible to replicate in the simulation without information on humidity or radiation variability.

We analyzed the modeled water flux at a depth of 350 cm, which represents the drainage from the soil column to the groundwater table, and compared the amount with the rainfall amount for each event. The groundwater table is variable, and one would need to look at the variable groundwater table to accurately reproduce the water flux. However, such a method would lead to additional research questions regarding the interaction of the groundwater table and infiltration, which is beyond the scope of the current paper. By focusing on the draining flux at a depth of 350 cm, the present study explored the possibility of groundwater recharge at the lowest groundwater level possible and the thickest soil layer in the hillslope, as observed in events #202 and #220.

Figure S5 shows that most of the precipitation discharged as drainage throughout the event duration. During high-intensity rainfall events, such as event #202 (Figure S6a), rainfall was quickly drained out to the groundwater table within a few hours when no decay of soil parameters was assumed (i.e. homogeneous soil layer). The pressure head profile during event #202 showed the fast progression of the wetting front due to a large pressure gradient and the near-saturation conditions of the entire soil column due to capillary effects. These results reinforce the hypothesis that vertical water percolation reaches the bottom of the thick subsoil layer within a relatively short time and contributes to the groundwater responses.

When exponential decay of soil properties was assumed, the discharge intensity was reduced and the response timing was slower at a depth of 350 cm (Figure S6a, b). However, the amounts of cumulative discharge at 350 cm were smaller only by 10% compared with those of a homogeneous soil layer. Moreover, the fluxes at a depth of 150 cm were still similar to those of a homogeneous soil layer. These results imply that even if the depth-decaying relationship is assumed based on the previous investigation at multiple forested hillslopes (Beven, 1982), the contribution of vertical infiltration is still possible where the surface soil is relatively thin, or when the groundwater table is at a shallow depth.

Although it is substantial, the simulated drainage is not enough to cause a 2–3 m rise in the groundwater table. If we neglect capillary effects, then to make up the soil moisture deficit of 0.07 cm$^3$/cm$^3$ assuming that the antecedent volumetric water content is 0.60 cm$^3$/cm$^3$ and the porosity is 0.67 cm$^3$/cm$^3$, 140 mm of total flux (2000 mm of soil layer $\times 0.07$ cm$^3$/cm$^3$ of soil moisture deficit = 140 mm of deficit) should be discharged to the groundwater table.

**DISCUSSION**

*Runoff generation processes in humid tropical forests*

The main contribution of this study is that it provides evidence that vertical infiltration through up to 3 m of loamy soils is a likely mechanism for fast (under 1 hour from rainfall onset) increases in groundwater level in a humid tropical catchment. In temperate regions, loam soil layers with low permeability usually impede or delay percolation such that the groundwater responses occur slowly or have small magnitudes (Wenninger et al., 2004; Duncan et al., 2016). As mentioned in the introduction section, in the humid tropics, soils that are rich in loam and clay content sometimes show high hydraulic conductivity; however, the relation between such soil properties and flow paths is still unclear. Our results provide new evidence from groundwater observations to support the hypothesis that tropical hillslopes with highly permeable soil layers consisting of fine particles (classified as loam to clay) promote fast vertical infiltration through the full depth of the soil profile (Dykes and Thornes, 2000; Noguchi et al., 1997a; 1997b). The results of our groundwater and one-dimensional infiltration simulation confirmed that vertical infiltration contributes substantially to an unconfined groundwater body. This conclusion is in line with the results of the tensiometer network observation made by Dykes and Thornes (2000) in Brunei and Noguchi et al. (1997b) in Malaysia that deep percolation leads to full saturation of thick soil layers and substantial responses of streamflow discharge. Regardless, our simulation results suggested that the amount of infiltrated water was insufficient to cause a 2–3 m rise in the groundwater table. Thus, an interaction between the infiltrated flow and the groundwater table would be anticipated.

Summarizing the results of this study as well as those of previous studies (Dykes and Thornes, 2000; Noguchi et al., 1997a; 1997b), we proposed the following underlying hillslope response mechanism in the study site (conceptualized in Figure 4). Even though the soil layer consists of loamy to clayey deposits that are approximately a few meters thick, the forest soil layer exhibited high hydraulic conductivity and water retention capacity. The unique soil hydraulic properties observed in the tropical environment (explained further in the next subsection) enabled the rapid transfer of significant amounts of rainfall water to the unconfined groundwater. The resulting groundwater responses depend on the rainfall characteristics as follows. During high-intensity rainfall events, in which wetting fronts could reach the groundwater table along the entire hillslope, groundwater responses are fast and large in magnitude (Figure 4a). Even if the depth-decaying relationship is strong, the wetting front might meet the groundwater table that has risen due to contribution from the upper slope; such interaction can cause significant responses in the groundwater table. On the other hand, during low-intensity rainfall events, in which interaction of wetting fronts and groundwater is limited around a thin part of the soil layer,
groundwater responses remain small (Figure 4b).

This hypothetical model can explain the observed response features summarized in Figure 3. The response times of groundwater during high-intensity events were similar to those during low-intensity events, possibly because the arrival timing of saturated subsurface flow (lateral flow) from upslope to downslope was similar both in high-intensity and low-intensity rainfall events. Meanwhile, the response magnitudes were enhanced in high-intensity rainfall events because vertical infiltration arrived as fast as lateral flow at SK1, and caused an interaction with the groundwater table, and enhanced the response magnitude.

To physically validate our conceptual model proposed in Figure 4, future studies should construct a two-dimensional infiltration model, or a two-dimensional lateral flow model combined with one-dimensional vertical infiltration. Other possible processes should be explored in future field investigations or modeling, such as groundwater seepage from weathered bedrock that would be contributing to stormflow generation (Kosugi et al. 2006), preferential flow network that could be attributed to fast infiltration in the humid tropics (Chappell, 2010), or return flow near the stream that could be pertinent to shallow groundwater. Furthermore, although not discussed in the results section, we observed a slight increase and decrease in the groundwater table at borehole SK3 during the no-rain period of May 2018 and that of September 2018, respectively. Some local water storage or perched water could be related to this observation, but more evidence is needed. Another limitation of this study was that we focused on subsurface processes. Previous studies suggested that the balance between transpiration and infiltrability plays a pivotal role in maintaining baseflow in the humid tropics (Bruijnzeel, 2004; Ghimire et al., 2014). Investigation into the role of vegetation for controlling evapotranspiration, canopy interception, and infiltration will be the critical steps to complete the process understanding and to predict the impacts of deforestation on hillslope hydrology.

Role of humid tropical soils in the runoff generation process

Another contribution of this study is that it demonstrated the unique properties of loam soil in humid tropical forests, and the high hydraulic conductivity and high water retention capacity, which possibly facilitated the fast and deep percolation. The fast drainage rate associated with humid tropical soils has been widely known in the field of soil or geochemical studies (Radulovich and Sollins, 1991; Six et al., 2002; Arya et al., 1998); however, little has been reported with respect to hydrology studies (Beven and Germann, 1982; Chappell et al., 2007). Such properties of tropical soils need attention from both local and global hydrologic models. First, in humid tropical hydrology, reference soil groups (Acrisol and Ferrosol end-member model by Elsenbein, 2001) or the existence of impeding layers that are low in permeability (Krishnaswamy et al., 2012) have been considered as the main controls of dominant flow paths. Our results offer another property of tropical soils that could play an important role in storm flow generation mechanisms. Second, in global hydrologic models, soil parameters are usually estimated using pedotransfer functions, which are based on the soil type (sand, clay, etc.) However, such parameterization cannot express soil hydrologic properties that are not typical of the soil type. Our results have important implications concerning the regionalization of global hydrologic models for the humid tropics.

The seemingly contradictory properties of tropical soil, high hydraulic conductivity and high water retention capacity, can be explained by the aggregate soil structure, which was visually observed both at the study site of the present study and that of Dykes and Thornes (2000). Humid climates and the presence of clay in soil facilitate the formation of stable aggregate structures, in that the soil drains water rapidly as sand and retains as much water as clay (Radulovich and Sollins, 1991). We reasoned that this aggregate structure was developed over the entire subsoil domain and promoted the fast and deep percolation observed in this study. This hypothesis should be confirmed in future studies via the measurement of matric potential and the evaluation of the spatial heterogeneity of soil properties at a larger scale (our soil experiments confirmed that the soil properties are similar along the hillslope up to a depth of 60 cm).

CONCLUSION

In this study, we conducted hillslope monitoring of soil
moisture and the groundwater table, and soil in situ and laboratory experiments, as well as numerical simulations of unsaturated infiltration to understand the subsurface runoff process in a thick tropical soil layer. Silty/loamy soils are usually not as permeable and do not allow rainwater to percolate into deeper soil layers. However, we detected (i) a shallow groundwater table at 1–2 m above the bedrock and the soil interface, and (ii) significant responses within that groundwater table associated with high-intensity rainfall events. The modeling of the unsaturated flow showed that the fast recharge of infiltrated water to the groundwater table is plausible. The high permeability and high water retention characteristics of the aggregated soil could explain the large infiltration and near-saturated condition of the soil layer. These findings emphasize the importance of subsurface flow recharged by vertical infiltration as well as the role of the tropical soil in this process. Overall, this study provides observational evidence to uncover runoff generation mechanisms in thick soil layers in humid tropical forests.

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SUPPLEMENTS

Text S1. Unsaturated flow modeling
Text S2. Outline of the modified Richards’ equation model
Text S3. Exponential relationship of soil parameters with depth
Figure S1. Photos of the study site
Figure S2. Results of soil experiments
Figure S3. Soil water retention curves
Figure S4. Observed and simulated variations in soil moisture content
Figure S5. Simulated cumulative water flux from a depth of 350 cm
Figure S6. Simulated draining water fluxes and the progression profile of pressure head
Table S1. Definition of rainfall, groundwater, and soil moisture metrics
Table SII. Response of the groundwater table
Table SIII. Calibrated soil hydraulic parameters in the HYDRUS-1D simulation

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