



Background

Objective and Site

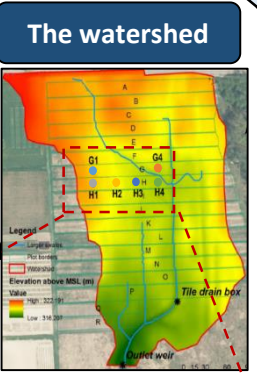
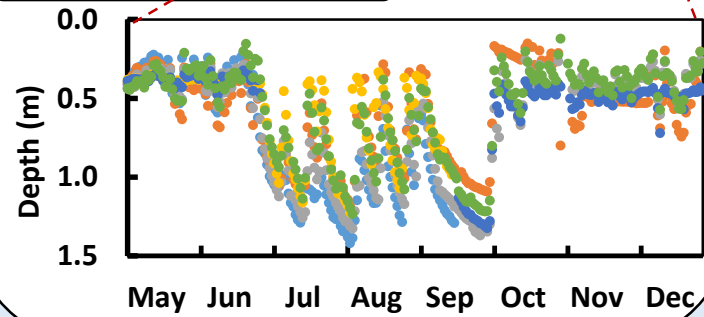
Discover the watershed self-organization principles needed for surrogate modeling.

A 5.4 ha periodically waterlogged watershed above a shallow perched water table in Ithaca.

Self organization

Spatially uniform piezometer response suggests self-organization of hydrological processes

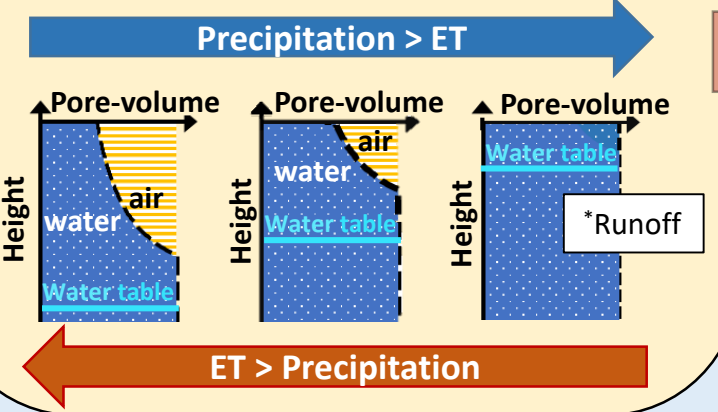
The Piezometers readings



Model

Self organization assumptions

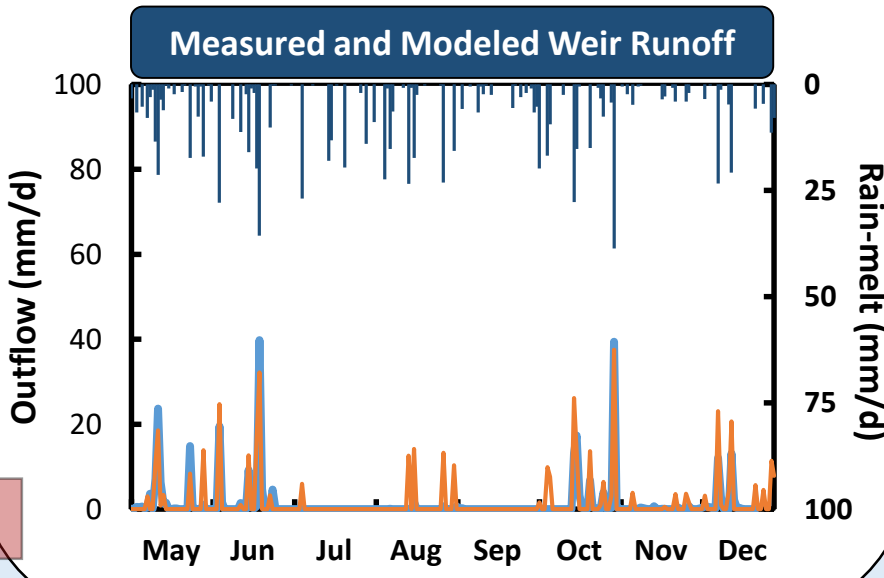
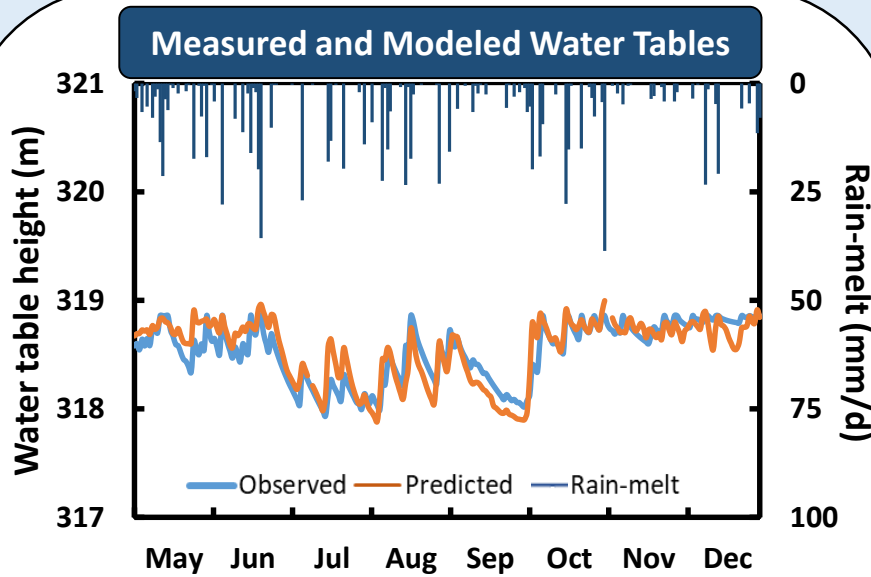
- Subsurface flow is negligible
- Water stops moving in less than a day when hydrologic potential is constant.
- Empty pore volume dependent on the soil characteristic curve and water table height
- Runoff occurs after soil is saturated



Conclusions

Self organization is a consequence of field reaching equilibrium each day. Equilibrium depends on soil characteristic curve, rain and evaporation that are spatially uniform.

Results



Modeling groundwater table and runoff in self-organizing hydrologically sensitive areas

Supporting material

The Study Site

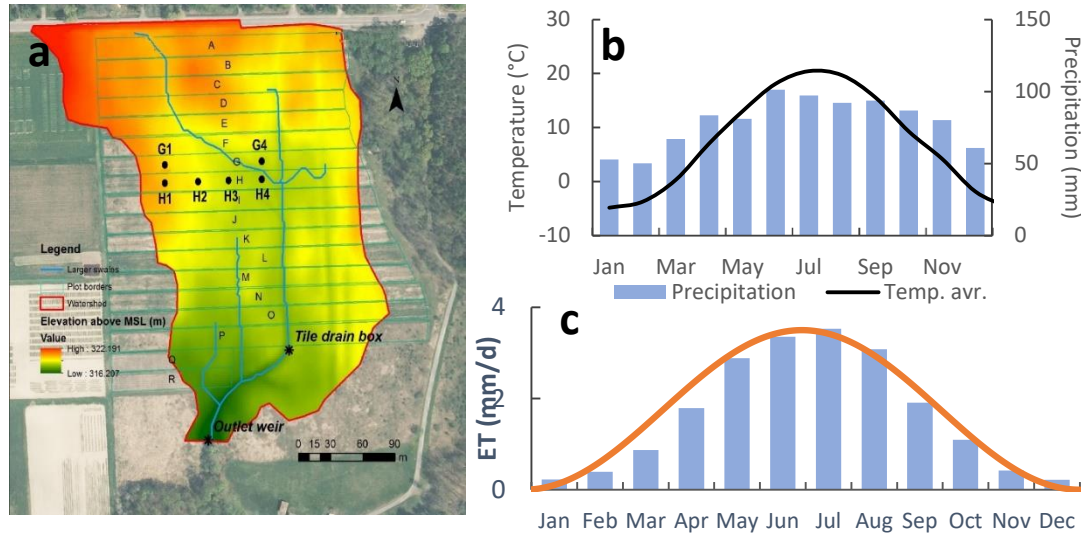


Figure 1. a) The Study site: A 5.4 ha, standalone watershed, near the Cornell University campus in Ithaca, New York USA (42° 28.23' N, 76° 25.96' W). **b)** The average monthly temperature and precipitation at the site. The regional climate is of a humid continental type, and the mean annual precipitation is 947 mm, with much falling as snow in the winter. **c)** Average monthly evapotranspiration (ET) in the site ranges from close to zero during December-January to 3.5 mm/d during June-July. A sinusoidal function was chosen to reflect this annual ET cyclic behavior.

The site is used to grow mostly switchgrass (*Panicum virgatum* v. Shawnee) for bioenergy cropping research. The site soil is clay loam with shallow fragipan atop a dense glacial till. Seasonally perched shallow water tables make the site periodically waterlogged, making the site a hydrologically sensitive area. A large weir was placed across the main swale outlet of the field to allow outflow measurements. Six piezometers (marked G1, G4, H1, H2, H3 and H4) equipped with dataloggers recorded the water table depth continuously.

Self organization in the site

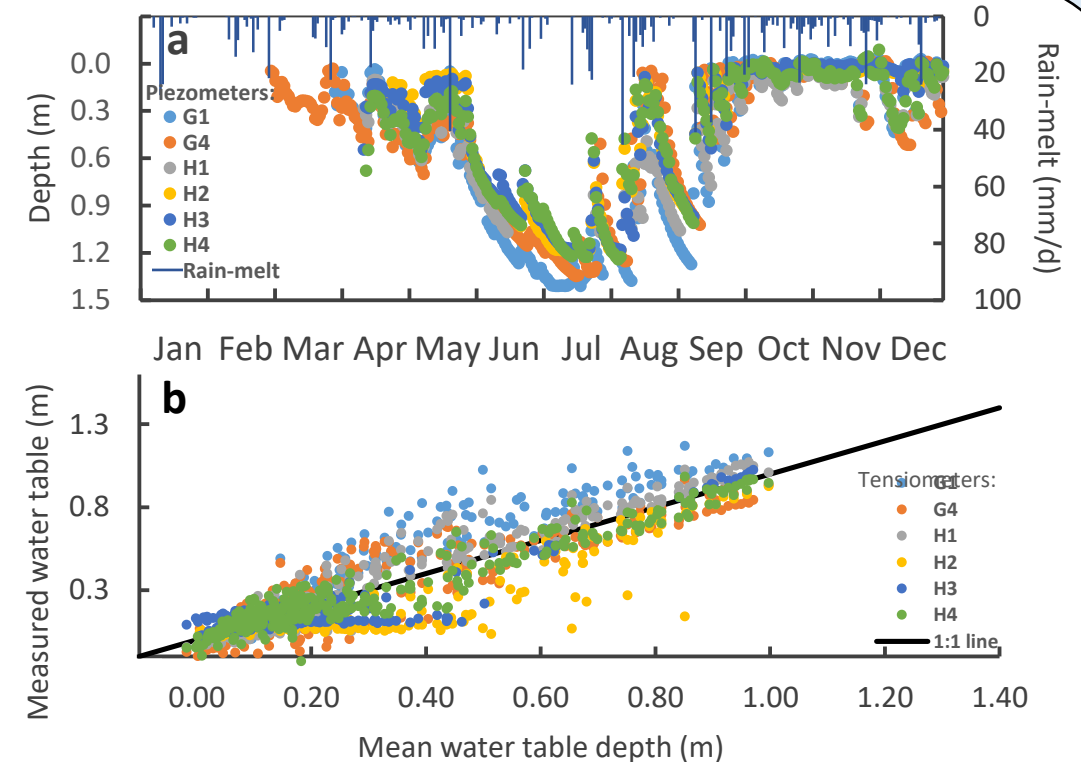


Figure 2. a) Daily water table depth in the piezometers. The water levels confirm the organized state of a hydrological sensitive area. Despite the different locations, the water levels follow the same pattern. **b)** Daily mean water table depth of the piezometers plotted against the individual daily water table depth of these six piezometers. Solid line represents the 1:1 line. The location of the piezometers is given in Figure 1a.

Figure 2b results are one outcome of the organized state of a hydrological sensitive area. Since the water table is similar throughout the field and runoff occurs when the field is saturated, runoff from rain can be simulated as if the field is homogenous.

Supporting material

Deficit from saturation

Deficit from saturation d : The quantity of water needed to saturate the soil, or, the volume of empty pores in the soil:

$$d = \int_0^h [\theta_s - \theta_{eq}(y)] dy \quad [1]$$

Where y is height above water table (L), h is the water table depth (L), θ_s is the saturation water content ($L^3 L^{-3}$), and $\theta_{eq}(y)$ is the equilibrium water content ($L^3 L^{-3}$).

The soil's deficit from saturation is tracked each day by subtracting the difference between precipitation and evapotranspiration from the previous day's deficit:

$$\begin{aligned} d(t) &= d(t - \Delta t) - [P(t) - ET(t)] \Delta t \quad \text{for } d(t - \Delta t) - [P(t) - ET(t)] \Delta t < 0 \\ d(t) &= 0 \quad \text{for } d(t - \Delta t) - [P(t) - ET(t)] \Delta t \geq 0 \end{aligned} \quad [2]$$

where $P(t)$ is the precipitation (rainfall plus snowmelt) ($L T^{-1}$), and $ET(t)$ is actual evapotranspiration ($L T^{-1}$), which in the late fall, winter, and early spring is equal to the potential evaporation in the northeastern US, and Δt is the time step (T).

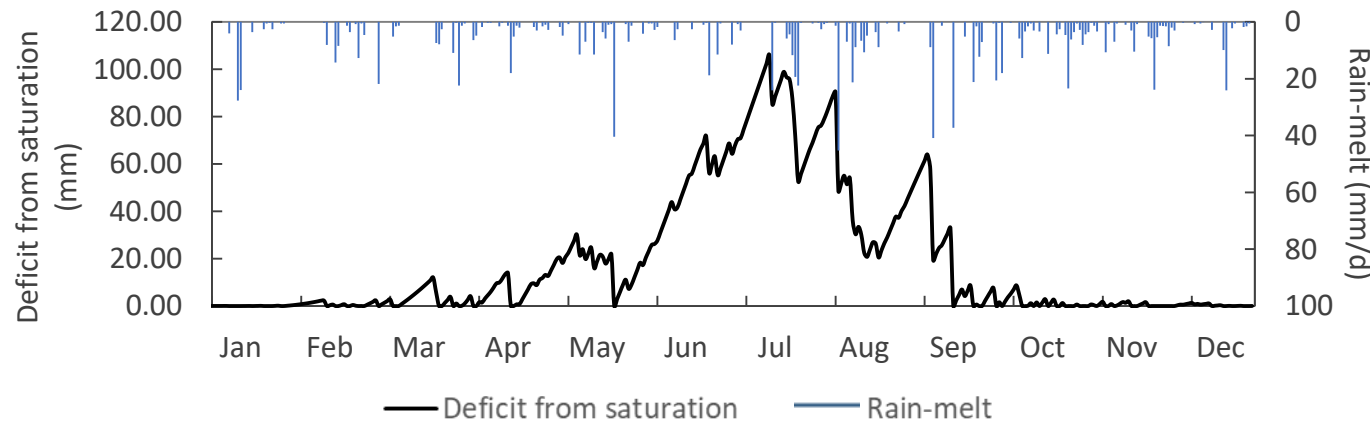


Figure 4. Example of daily deficit from saturation in the watershed during 2018. Increasing values of $d(t)$ in time indicate that as the drainable porosity increases, the soil dries, and the water table drops. In contrast, decreasing values imply a deficit reduction from saturation as the water table rises. When $d(t)=0$, saturation conditions are reached, and runoff can occur.

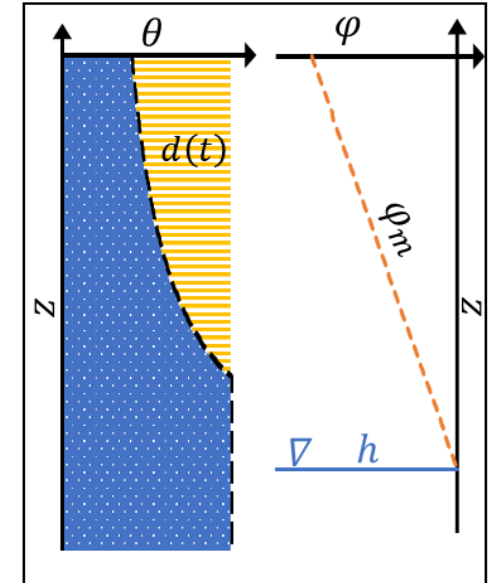


Figure 3. Schematic representation during soil water equilibrium of $d(t)$. Above the water table the sum of matric potential, ϕ_m , and gravity potential are constant, thus the matric potential, ϕ_m (dashed orange line), is linear with depth z . θ , (dashed black line) is the equilibrium moisture content. The blue area represents the water in the soil and the deficit from saturation, $d(t)$, is the yellow striped area.

Supporting material

Soil characteristic curve and deficit from saturation

The deficit from saturation, d , in the soil calculated with Eq. 1 corresponds to water table depth, h , and can therefore be used to calculate the water table depth. The relationship between deficit and water table depth is found by describing the equilibrium water content in Eq. 1 with its description according to the Brooks and Corey model:

$$\begin{aligned} \theta_{eq} &= \theta_r + [\theta_s - \theta_r] \left[\frac{y}{\varphi_b} \right]^{-\lambda} & \text{for } |y| > |\varphi_b| \\ \theta_{eq} &= \theta_s & \text{for } |y| \leq |\varphi_b| \end{aligned} \quad [3]$$

where θ_r is the residual moisture content ($L^3 L^{-3}$), φ_b is the bubbling pressure head (L), and λ is the pore size distribution index (dimensionless).

Combining Eq. [3] with Eq. [1], integrating and noting that $y = h - z$, yields the following expression for water table depth vs. deficit from saturation:

$$\begin{aligned} d &= [\theta_s - \theta_r] \left[h - \frac{h}{-\lambda + 1} \left[\frac{h}{\varphi_b} \right]^{-\lambda} + \frac{\lambda}{-\lambda + 1} \varphi_b \right] & \text{for } h > |\varphi_b| \\ d &= 0 & \text{for } h \leq |\varphi_b| \end{aligned} \quad [4]$$

The constants $\theta_s, \theta_r, \varphi_b$ and λ of the Brooks and Corey water retention function for the clay loam soil at the study site were estimated using the Rawls and Brakensiek (1985) pedotransfer functions.

Comparing measured d vs h to Eq. 4 predictions reveals good agreement. However, since the water table height h in Eq. 4 could not be written as an explicit function of the deficit d , a simpler $h'(d)$ equation was fitted to equation 4. The new equation:

$$h' = 8.3 \cdot d^{0.6} + \varphi_b \quad [5]$$

has an R^2 of 0.98 to the original Brooks and Corey equation (Figure 5).

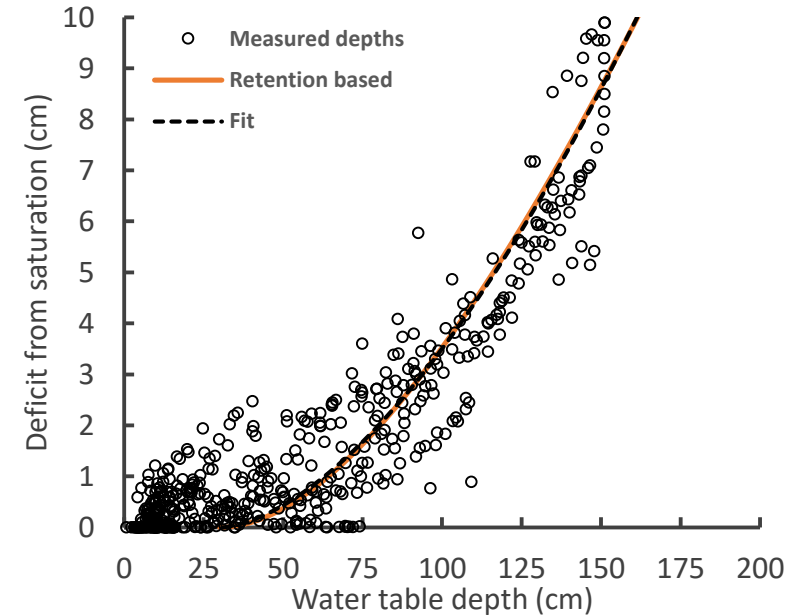


Figure 5. The calculated deficit from saturation vs water table height relations based on measured piezometer data (circles), the soil characteristic curve in Eq. 4 (solid orange), and fitted power equation (dashed black).

Supporting material

Predictions of water table heights and daily runoff

Daily water table heights

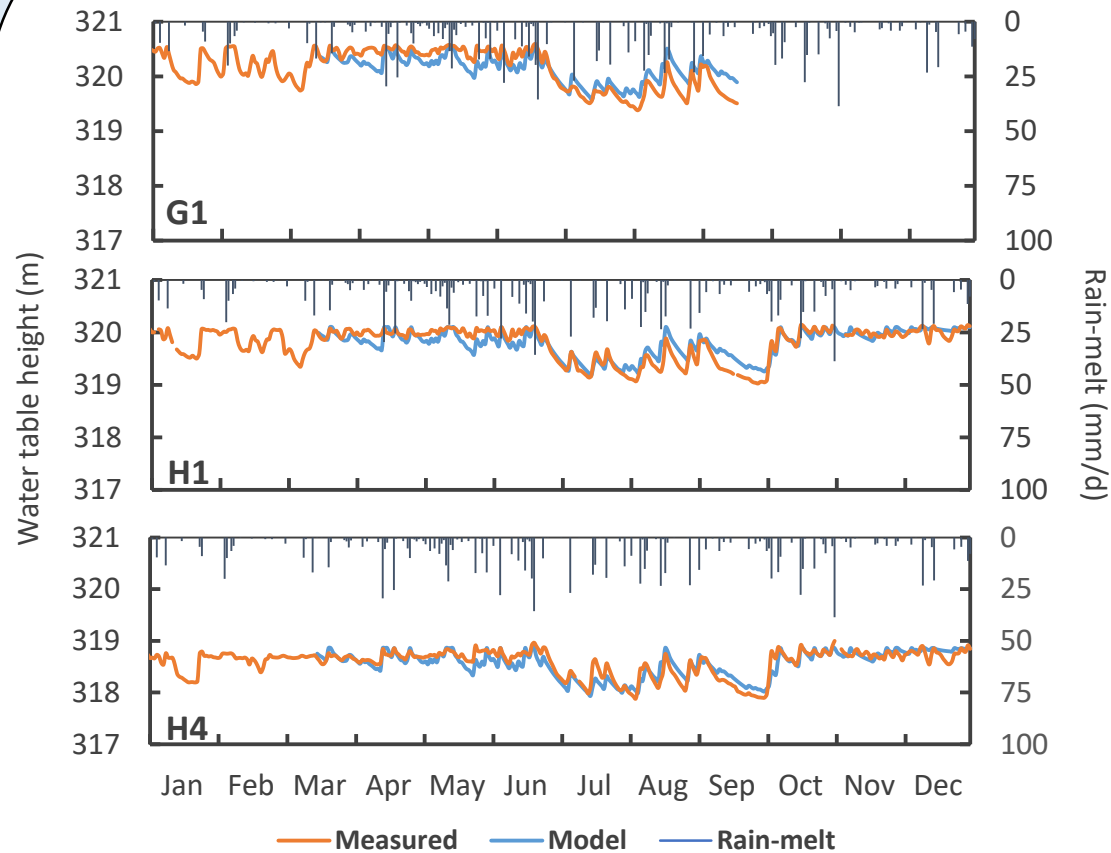


Figure 6. The annual water table for piezometers G1, H1 and H4 (orange), and predicted (blue) results for same piezometers during 2019. Rain and melt water measurements are also presented in each figure as hanging column.

Daily runoff

Runoff for each day was determined by the water content in the soil, the amount of precipitation, and evaporation. When rainfall is greater than what the soil can store, the excess becomes runoff; otherwise, there is no runoff. This is expressed as:

$$R = \begin{cases} 0 & \text{for } d(t) \geq 0 \\ [P(t) - ET(t)]\Delta t - d(t) + d(t - \Delta t) & \text{for } d(t) < 0 \end{cases} \quad [6]$$

where R is the runoff ($L T^{-1}$).

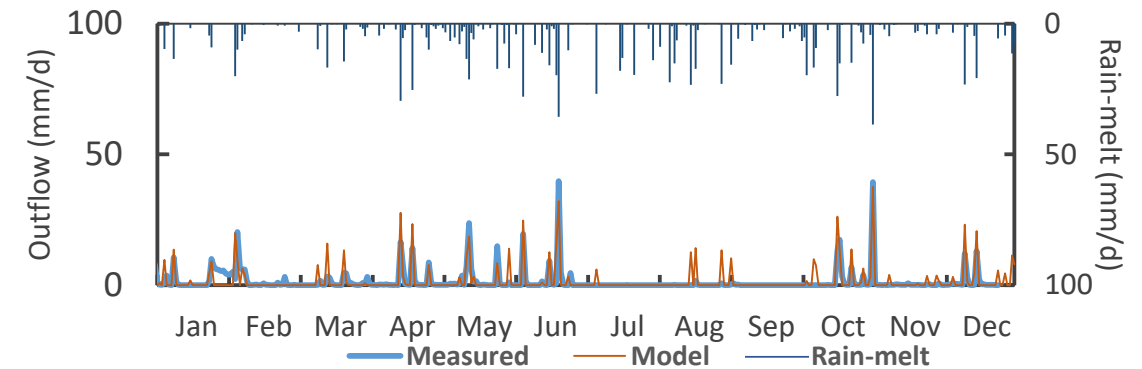


Figure 7. The daily predicted runoff (orange), the observed outflow at the weir (blue) during 2019, and the daily rain and snowmelt are also presented as a hanging column. All the data is normalized to water column height.

Supporting material

For additional data on the Field

- Das, S., Richards, B.K., Hanley, K.L., Krounbi, L., Walter, M.F., Walter, M.T., Steenhuis, T.S., Lehmann, J., 2019. Lower mineralizability of soil carbon with higher legacy soil moisture. *Soil Biol. Biochem.* 130, 94–104. <https://doi.org/10.1016/j.soilbio.2018.12.006>
- Das, S., Teuffer, K., Stoof, C.R., Walter, M.F., Walter, M.T., Steenhuis, T.S., Richards, B.K., 2018. Perennial grass bioenergy cropping on wet marginal land: Impacts on soil properties, soil organic carbon, and biomass during initial establishment. *BioEnergy Res.* 11, 262–276. <https://doi.org/10.1007/s12155-018-9893-4>
- Mason, C.W., Stoof, C.R., Richards, B.K., Rossiter, D.G., Steenhuis, T.S., 2016. Spring-thaw Nitrous Oxide emissions from Reed Canarygrass on wetness-prone marginal soil in New York state. *Soil Sci. Soc. Am. J.* 80, 428–437. <https://doi.org/10.2136/sssaj2015.05.0182>
- Richards, B.K., Stoof, C.R., Mason, C., Crawford, R. V, Das, S., Hansen, J.L., Mayton, H.S., Crawford, J.L., Steenhuis, T.S., Walter, M.T., others, 2013. Carbon sequestration and gaseous emissions in perennial grass bioenergy cropping systems in the Northeastern US: Proceedings of the AAIC Meeting USDA-NIFA Session on Carbon Sequestration and Greenhouse Gas Emissions from Bioenergy Crops, Washington, DC, USA. Washington.
- Richards, B.K., Pacenka, S., Meyer, M.T., Dietze, J.E., Schatz, A.L., Teu, K., Aristilde, L., Steenhuis, T.S., 2018. Antecedent and Post-Application Rain Events Trigger Glyphosate Transport from Runoff -Prone Soils. <https://doi.org/10.1021/acs.estlett.8b00085>