Stochastic weather generators coupled with soil physics models for rare-event estimation: application to groundwater recharge in Nevada (USA)

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Abstract

Episodic rare precipitation events of high intensity strongly shape groundwater recharge and water availability in arid regions, yet projections of climate impacts on subsurface hydrology often rely on averaged (monthly or seasonal) predictions. We investigate how rare-event probabilities of groundwater recharge derived from scale-aware, stochastic boundary conditions compare with those obtained from temporally averaged forcings. Here we coupled an hourly stochastic weather generator with two vadose-zone simulators to represent decadal results from an experimental facility near Las Vegas, Nevada. Meteorological boundary conditions are produced using AWE-GEN (Advanced WEather GENerator), an hourly stochastic weather generator combining empirical statistical relations and physically-based components. From these outputs, we compute potential evapotranspiration with FAO-56 Penman–Monteith. With these inputs, we simulated groundwater recharge using two alternative vadose zone models: (i) SEC (Surface Evaporation Capacitor), a bucket model of near-surface storage and fluxes that includes state-of-the-art understanding of soil evaporation processes; and (ii) HYDRUS-1D, a Richards-equation solver for layered media allowing the simulation of detailed unsaturated-zone dynamics, where evapotranspiration is handled by the upper boundary condition for soil evaporation and a distributed sink term for root water uptake inside the soil profile. The case study focuses on the unique SEPHAS observatory that includes long-term records of weighted lysimeters and TDR-based soil moisture, as well as meteorological variables in terms of radiation, humidity, temperature, wind, and precipitation. After calibrating AWE-GEN to this site, we evaluate SEC and HYDRUS across (a) recharge frequency distributions and event magnitudes, (b) seasonal evaporation partitioning and potential evapotranspiration consistency during energy-limited periods, and (c) sensitivity to soil parameters and upper/lower boundary conditions. Next, we plan to focus on rare-event metrics, such as annual groundwater-recharge exceedance levels, multi-week Stage-II (soil-limited) evaporation durations, and extreme rainfall thresholds. To target rare

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event probabilities efficiently, we incorporate Adaptive Multilevel Splitting (AMS), a rare-event simulation method from probability/statistical physics, in our modeling framework. This technique adaptively concentrates computation on trajectories that approach the rare event by cloning those that make progress and pruning those that do not while accounting for probabilities using importance sampling theory.

Keywords: Groundwater recharge Rare events Extreme precipitation Stochastic weather generator (AWE, GEN) Vadose zone modeling (SEC, HYDRUS, 1D) Adaptive Multilevel Splitting (AMS) Evapotranspiration (FAO, 56 Penman–Monteith) Arid regions (Nevada, SEPHAS)