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From point to slope: Measured and modeled scale effects of Hortonian surface runoff in West Africa

N van de Giesen (1,5), A Ayodele (2,5), F Bagayoko (3,5), TJ Stomph (4)

(1) Delft University of Technology, Netherlands (n.c.vandegiesen@tudelft.nl), (2) Federeal University of Technology Akure, Nigeria, (3) Institut International d'Ingénierie de l'Eau et de l'Environnement, Burkina Faso, (4) Wageningen University and Research Centre, Netherlands, (5) Center for Development Research (ZEF), Germany

The percentage of rainfall that runs off from a slope tends to decrease with the length of the slope. This scale effect has been reported on for many semi-arid regions in the world. Here, we present a set of field measurements from West Africa from the forest zone (Ghana), the Guinea savanna (Côte d'Ivoire), and the Sudan savanna (Burkina Faso). In each case, surface runoff was Hortonian, that is to say, it was produced because rainfall intensities exceeded the infiltration capacity of the soils. Typically, rainstorms in West Africa are of short duration (20-40 minutes), with high intensities (50-150 mm/hr). Rainfall intensities were measured with tipping-bucket gauges.

The experimental set-up was comparable for all three cases. In each case, runoff plots of different lengths were installed and total runoff after each rainfall event was measured. At the Ghana site, plot hydrographs were measured as well with tipping buckets. In addition, a laboratory flume was built to have a controlled environment to test models.

The measurements all showed a decline in runoff coefficients with increasing slope length. In order to better understand this phenomenon, models were developed. Infiltration was modeled with the Philip-Two-Term model and the Time Compression Algorithm. The slopes of the flume, in Côte d'Ivoire, and in Burkina Faso were relatively flat (2% to 6%) and smooth. For these circumstances, a simple 1-D kinematic wave model was sufficient to simulate the surface runoff. The slopes in Ghana were steeper ($>$6%) and had a very strong micro-topography and a special numerical scheme was developed to deal with this case.

The models confirmed that it is in first instance temporal dynamics that determine the existence of observed scale effects. Because rainstorms tend to be of short duration, most of the water collected on the surface will not have reached the bottom of the slope once the rainfall stops. This water will quickly infiltrate once the rain ends. Only when the rainstorm is long enough so that the slope reaches equilibrium, does the scale effect disappear. The time to equilibrium tends to increase with an increase in spatial variability of infiltration and topographical characteristics.

From both direct observation and the model outcomes, it is clear that in modeling surface runoff in West Africa, one can not simply multiply 1-D point infiltration with slope lengths to obtain watershed runoff.