Land cover effects on surface runoff generation in Eastern Madagascar

Ilja van Meerveld, Chandra Prasad Ghimire, Bob W. Zwartenjik, Maafka Ravelonana, Jaona Lahitiana, Sampurno Bruijnzeel

Introduction
Reforestation is promoted for a wide range of benefits, including carbon sequestration, biodiversity, rehabilitation of degraded land and streamflow regulation. However, surprisingly little is known about how reforestation of degraded land impacts water resources. Reforestation may lead to an increase in soil organic carbon and the re-establishment of roots and soil biodiversity, which increase the hydraulic conductivity of the soil. This may lead to a decrease in overland flow and an increase in recharge. As part of our study on the effects of land use on water resources in the Corridor Ankeniheny-Zahamena (CAZ) in Madagascar, we studied how land use affects the partitioning of precipitation into surface runoff and recharge, and what controls the occurrence of surface runoff.

Methods
We installed research plots in a closed canopy forest, a reforested tree fallow and a degraded grassland site. At each plot we measured rainfall, throughfall (66 gauges and 3 gauges per forest site and surface runoff (1 to 3 by 10 m runoff plots per site) between 1.10.2014 and 30.09.2015. All drums and gauges were emptied daily. Soil moisture was measured continuously at 4, 4.6 depths below the soil surface. Perched groundwater levels were measured in piezometers installed at 30 cm below the soil surface. Soil moisture storage in the top 27.5 cm of the soil profile was determined by multiplying the volumetric moisture content by the distance between the sensors. The soil moisture deficit was determined for each event by subtracting the pre-event soil moisture storage from the maximum soil moisture storage. Surface and near-surface saturated hydraulic conductivities were measured in situ at 5 points and 3 depths in each plot.

Surface runoff, soil moisture and perched groundwater levels
There was more surface runoff at the degraded grassland site than at the reforested fallow or closed canopy forest site. Significant surface runoff occurred only when soil moisture was high, particularly during large events at the end of the wet season. Perched groundwater levels were common during this period and reached almost the soil surface. This occurred most frequently at the degraded site.

Threshold for surface runoff generation
There was a clear threshold relation between the amount of surface runoff and the net precipitation minus the soil moisture deficit. These results suggest that the near surface soil needs to become saturated before surface runoff occurs. After saturation, surface runoff was approximately 23% of precipitation at the degraded site and 14% of throughfall at the forested sites. Rainfall intensity did not affect this relation.

Saturated hydraulic conductivity (K_sat)
Near surface K_sat was lowest for the degraded site and decreased rapidly with depth below the soil surface. K_sat at 20-30 cm depth was less than the 95th percentile of the 15-mm precipitation intensity. Note that 40% of the annual rainfall fell at an intensity higher than the 95th percentile.
Measurements at 45 other sites across CAZ showed a similar variation in K_sat with land use and depth below the soil surface.

Summary
- Reforestation leads to a reduction in surface runoff due to the increase in K_sat of the near surface layers. However, this reduction was small compared to the interception losses, so that reforestation does not necessarily increase the amount of water that infiltrates into the soil.
- The soil moisture deficit and net precipitation determine the amount of surface runoff.
- The low saturated hydraulic conductivity at 20-30 cm depth causes perched groundwater tables that (almost) reach the soil surface during large rainfall events at the end of the wet season. This leads to saturation overland flow.
- Near surface K_sat values were much larger than the rainfall intensities. Surface runoff was not affected by the rainfall intensity. Infiltration excess overland flow is thus unlikely, even for the degraded site.
- A relatively simple bucket model may be sufficient to describe surface runoff generation in this area.

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