Effect of forest regeneration on saturated soil hydraulic conductivity and surface runoff in upland Eastern Madagascar

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Background

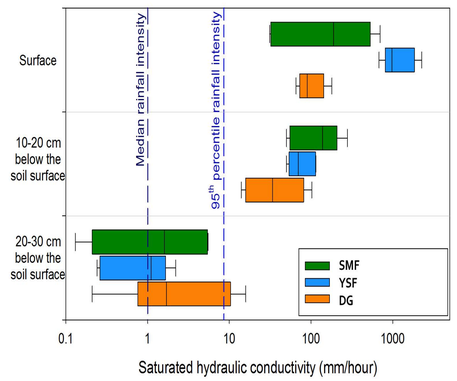
Secondary forests are ubiquitous across the tropics nowadays. Yet, surprisingly little is known about how natural or aided forest regeneration in severely degraded landscapes ultimately impact water resources. As part of a larger project investigating the effects of land degradation through intensive slash and burn cultivation and forest recovery on hydrological processes and the streamflow regime in upland Eastern Madagascar, this work documents the partitioning of precipitation into surface runoff and infiltration, the dominant pathways of infiltration, and the chief controls of the occurrence of surface runoff.

Methods

Research plots were established in degraded fire-climax grassland (DG), young secondary forest with aided reforestation (YSF, 5–7 years, LAI = 1.8), and semi-mature secondary forest (SMF, ≥20 years, LAI = 3.4) in the Ankeniheny-Zahamena Corridor (CAZ) at an average elevation of ca. 1000 m. Daily rainfall, throughfall (66 manual gauges and 3 recording gutters per forest site), stemflow and surface runoff (2-3 runoff plots of 3 m x 10 m per site) were measured between October 2014 and September 2015. Soil moisture content was measured continuously at 4–6 depths allowing evaluation of variations in soil moisture storage. Perched groundwater levels were measured in piezometers installed at 30 cm depth. Soil moisture deficits for each runoff event were determined by subtracting pre-event moisture storage from the maximum observed soil moisture storage. Surface and near-surface saturated soil hydraulic conductivities (K_{sat}) were measured *in situ* at 5 points and 3 depths per plot using double-ring and constant-head field permeametry, respectively. Preferential infiltration pathways were studied through blue-dye sprinkling experiments.

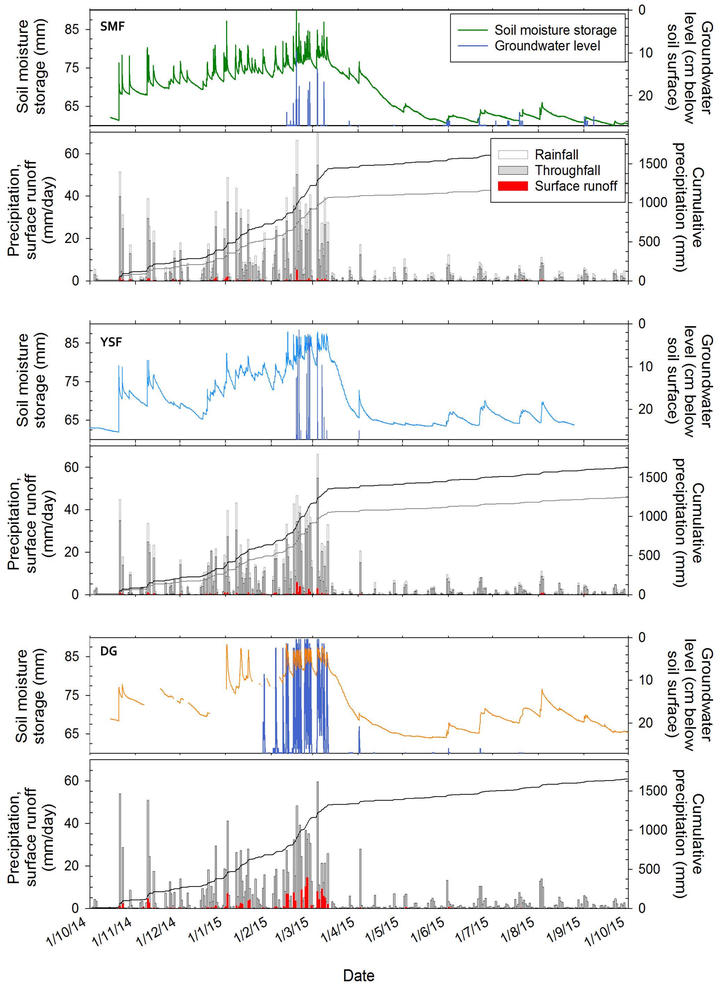
Saturated hydraulic conductivity (K_{sat})

Near-surface K_{sat} was lowest for the degraded grassland and decreased rapidly with depth. K_{sat} at 20-30 cm depth was less than the 95th percentile of the 15-min precipitation intensity (8.6 mm/h), while almost 40% of the annual rainfall exceeded this value. Measurements at 45 other sites across the CAZ showed a similar variation in K_{sat} with land cover and depth below the surface.



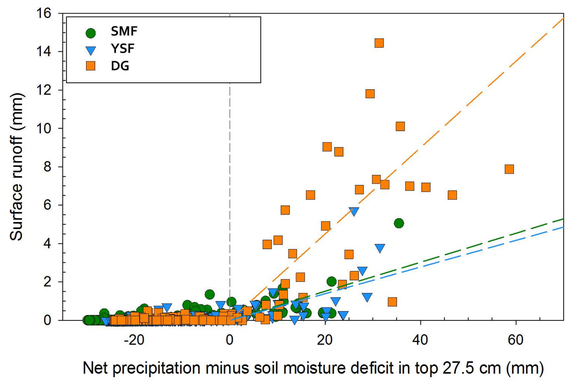
Surface runoff, soil moisture and perched groundwater

Surface runoff was greater in the degraded grassland than in the two regenerating forests. Significant runoff occurred only when soil moisture levels were high, particularly during large rainfall events late in the wet season. Perched groundwater levels were common during this period and close to the surface (most often in the degraded grassland).



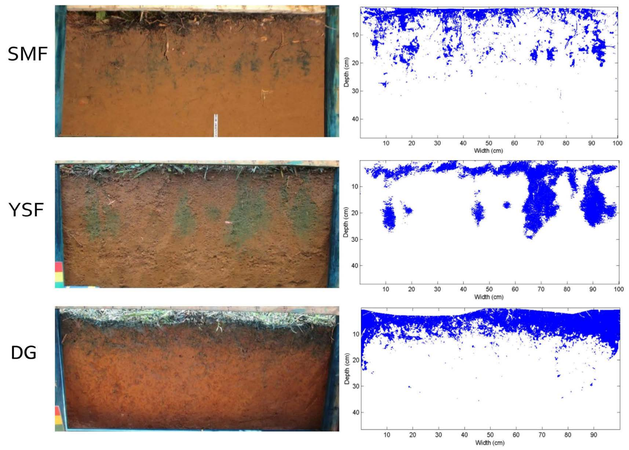
Threshold for surface runoff generation

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 22% of precipitation at the degraded site and 7% of throughfall at the forested sites. Rainfall intensity did not affect this relation.



Infiltration pathways

Infiltration was dominated by preferential flow in the SMF and by more uniform matrix flow in the near surface soil layers at the DG, while the YSF showed a mixed pattern.

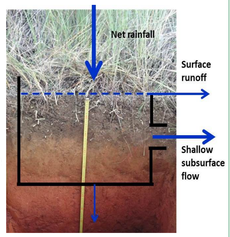


	Forest*	Reforested tree fallow	Degraded land
Tree age (years)	≥ 20	5-7	-
Throughfall (%)	71	76	-
1.10.2014 - 30.9.2015 (total rainfall: ~1675 mm)			
Total surface runoff (mm)	33	36	179
Surface runoff (% of precipitation)	1.9	2.2	10.9
Surface runoff (% of throughfall)	2.7	2.9	-
15.2.2015 – 14.3.2015 (total rainfall: ~550 mm)			
Total surface runoff (mm)	12	20	124
Surface runoff (% of precipitation)	2.8	4.5	24.0
Surface runoff (% of throughfall)	2.1	3.6	-

*Heavily logged and replanted but never clear-cut or burned

Summary

- Forest regeneration led to a reduction in surface runoff by ca. 145 mm yr^{-1} due to an increase in K_{sat} of the near-surface layers. However, this was counteracted by interception losses from the forest (290 and 475 mm yr^{-1} for SMF and YSF, respectively). Hence, forest regeneration did not necessarily increase the amount of water infiltrating.
- Infiltration predominantly followed preferential pathways in the semi-mature forest but showed more uniform matrix flow in the grassland and a mixture in the young secondary forest.
- Near-surface values of K_{sat} were much larger than most rainfall intensities. Surface runoff amount was not affected by rainfall intensity. Infiltration-excess overland flow was thus unlikely, even in the degraded grassland.
- The balance between soil moisture deficit and net precipitation input determined amounts of event surface runoff regardless of land cover.
- Low K_{sat} at 20–30 cm depth caused perched groundwater tables that (almost) reach the surface during large rainfall events late in the wet season. This led to saturation-excess overland flow.
- A simple bucket-type model may be sufficient to describe surface runoff generation in this area.



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