Combining field data and spatially distributed modelling

to understand the effects of land cover, soil degradation, and climate variability on the hydrological response of a meso-scale catchment in Eastern Madagascar

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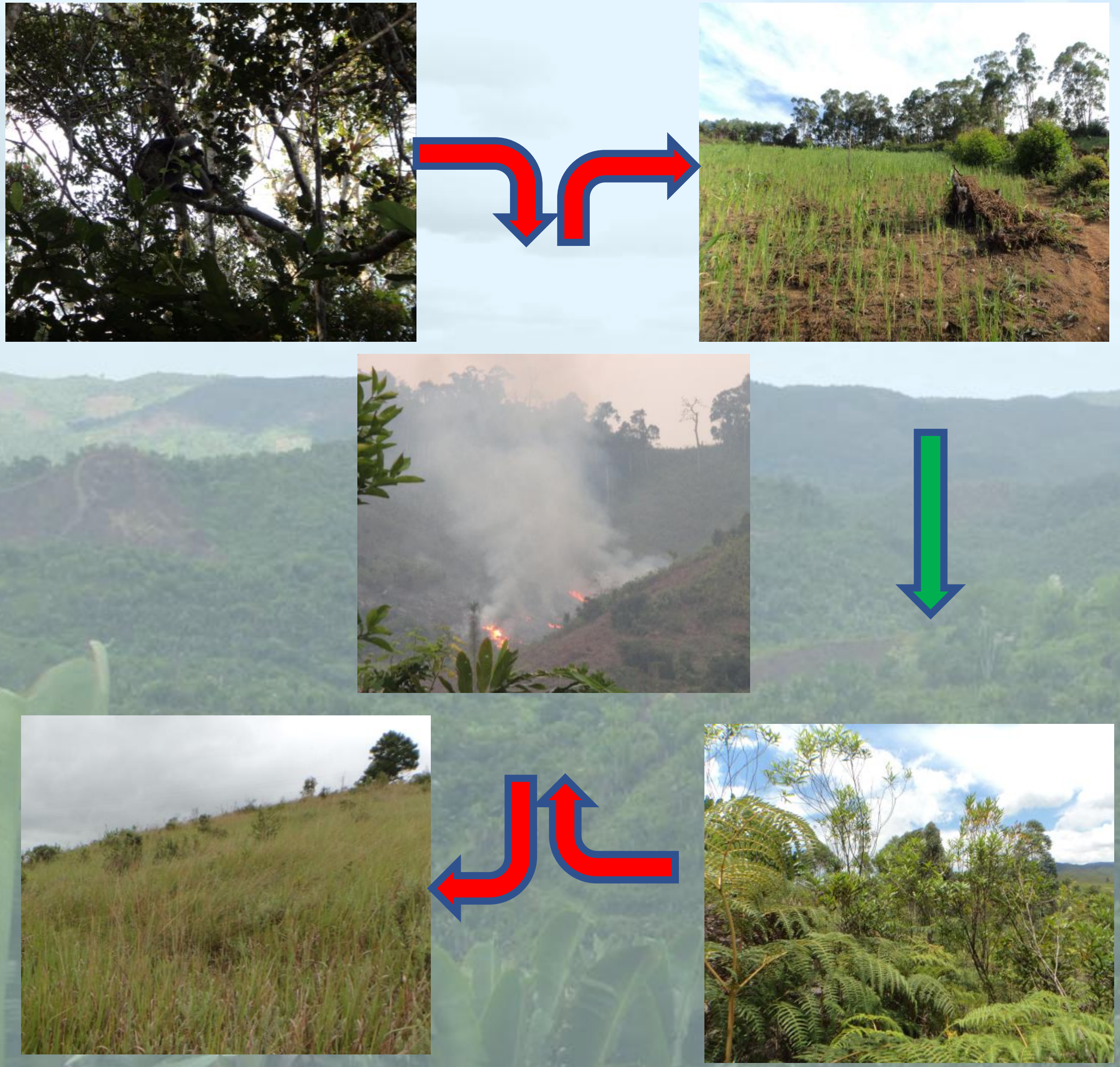
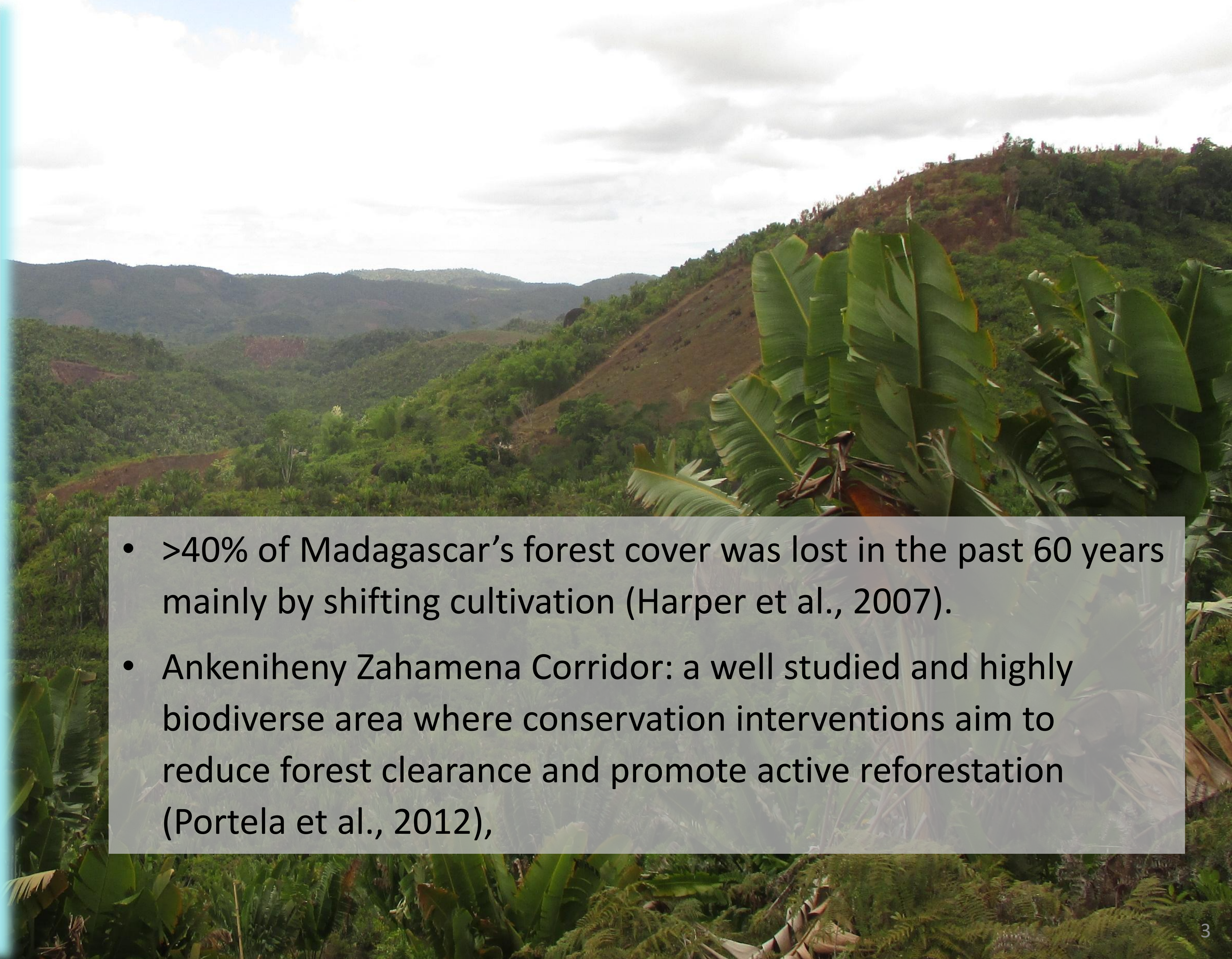
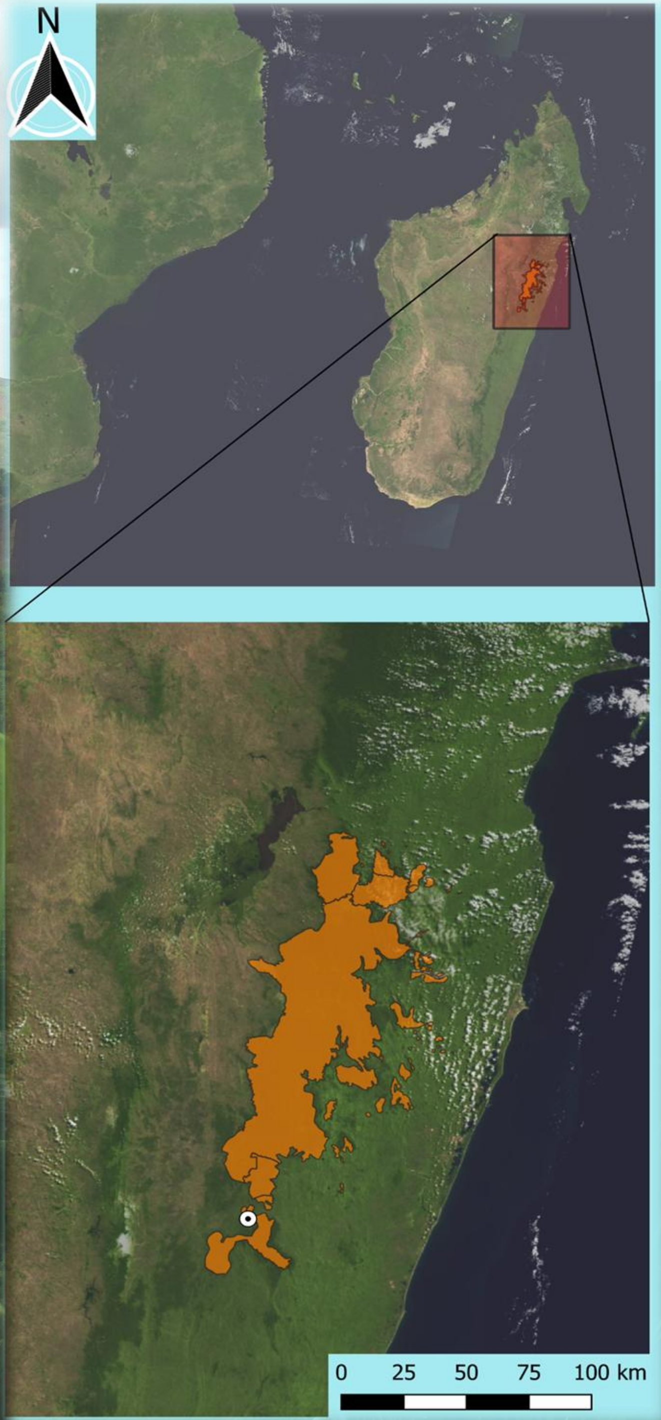


Shifting cultivation is the dominant agricultural system in the tropics

- Leading to a mosaic of land uses
- Repeated burning decreases soil biodiversity, soil organic carbon content, rooting depth and density, and the infiltration capacity



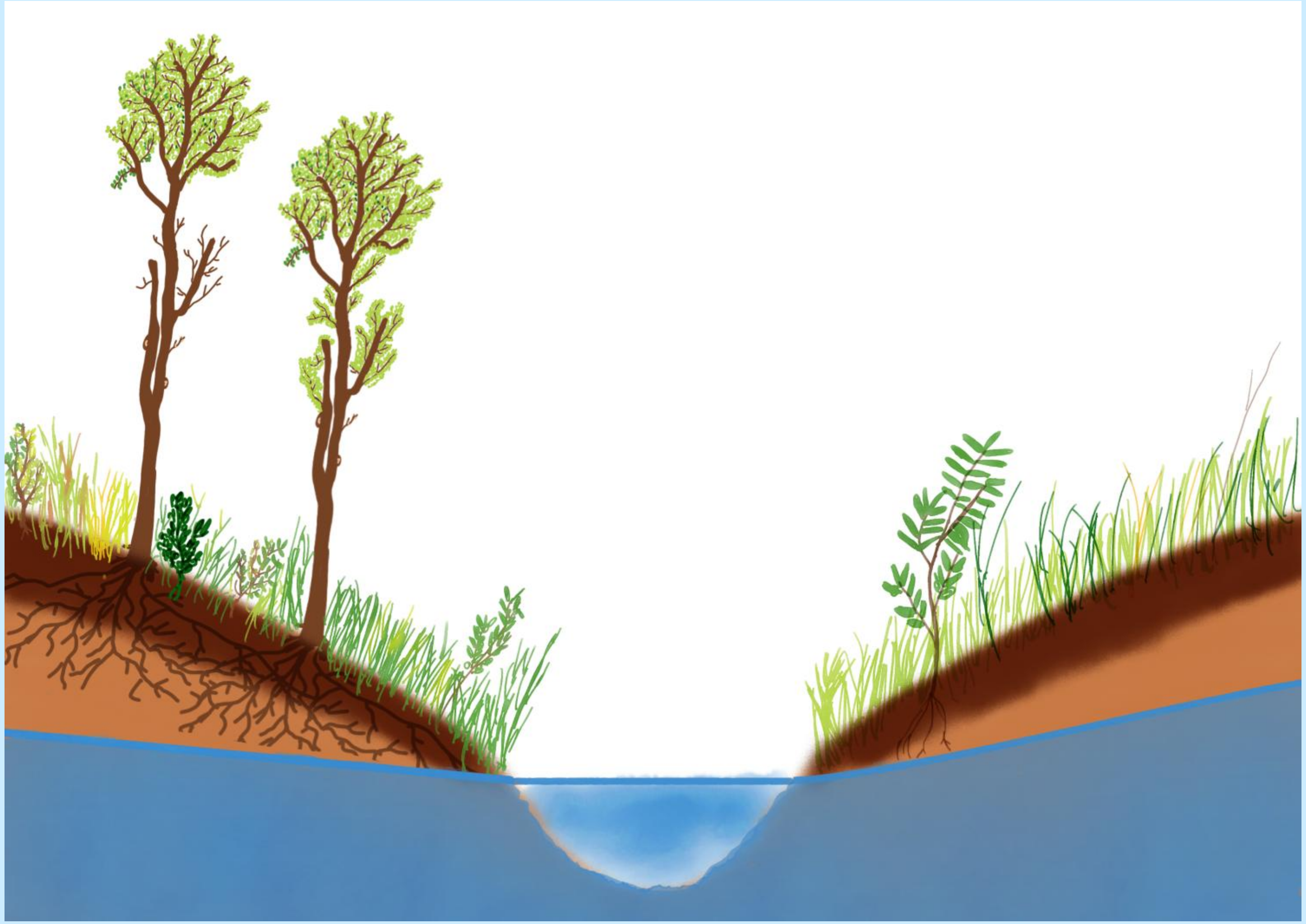


- >40% of Madagascar’s forest cover was lost in the past 60 years mainly by shifting cultivation (Harper et al., 2007).
- Ankeniheny Zahamena Corridor: a well studied and highly biodiverse area where conservation interventions aim to reduce forest clearance and promote active reforestation (Portela et al., 2012),

Runoff processes

Small rainfall event and/or dry antecedent conditions:

- Only rainfall on stream, wetlands and rice paddies reaches catchment outlet as event water;
- No to minor perched water tables on the hillslopes.

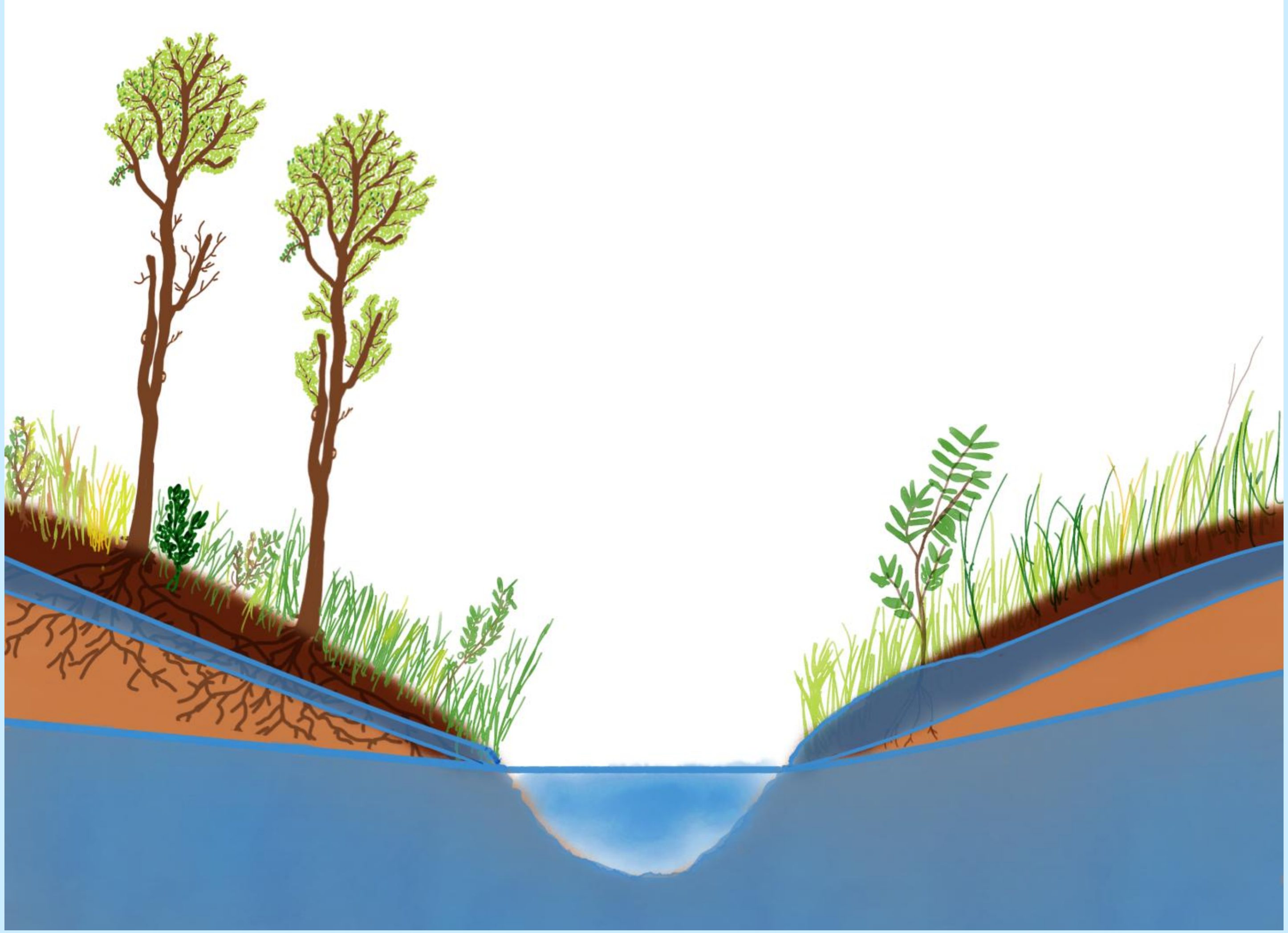


Zwartendijk et al. 2020 and 2023

Runoff processes

Larger rainfall events and/or dry to moist antecedent conditions:

- Some perched water tables on the hillslopes;
- Saturation excess overland flow at degraded sites and in the riparian zone;
- Stream flow dominated by pre-event water.

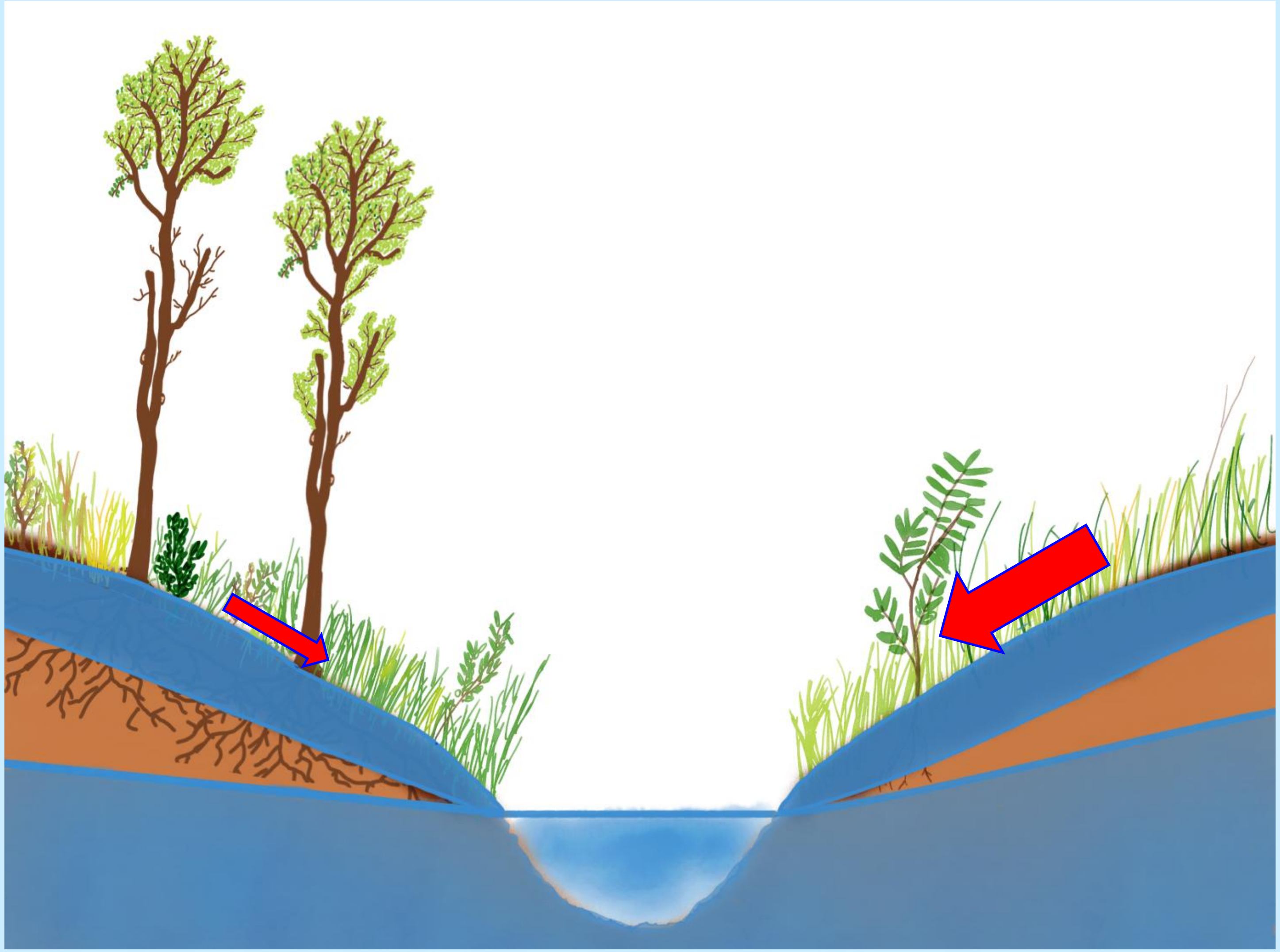


Zwartendijk et al. 2020 and 2023

Runoff processes

Very large rainfall event: and/or wet antecedent conditions:

- A large part of catchment is hydrologically connected to stream via perched water tables;
- Saturation excess overland flow also from upslope areas;
- Event-water dominates stream flow.

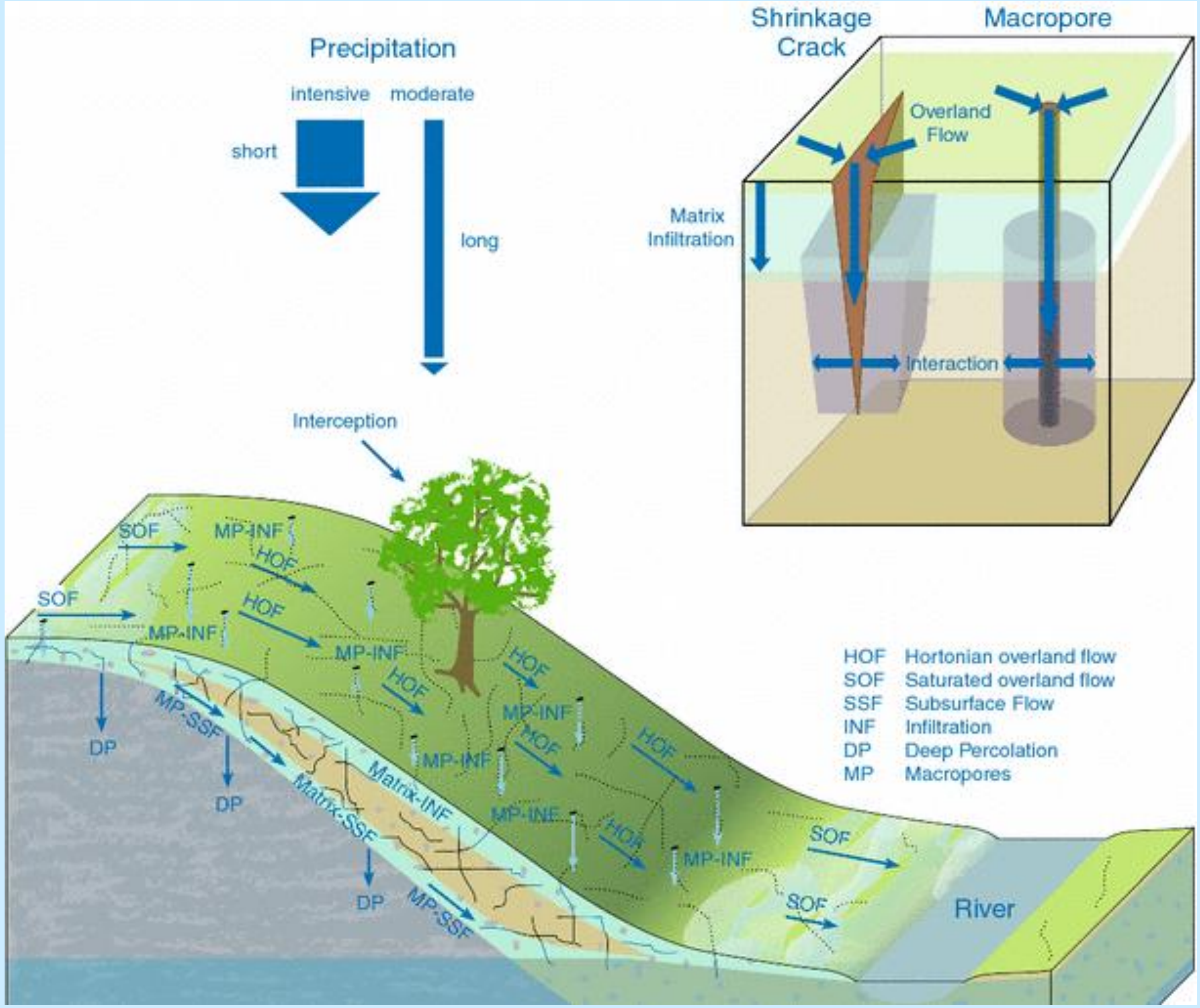


Zwartendijk et al. 2020 and 2023

Research questions

- What are the effects on land cover and soil degradation to stormflow and groundwater recharge?
- Will large scale afforestation decrease stormflow and enhance groundwater recharge?
- Does afforestation on foot slopes have a larger impact than afforestation on upslope areas?
- To what extent does climate variability affect stormflow and groundwater recharge?

Hydrological model



Steinbrich et al. 2016

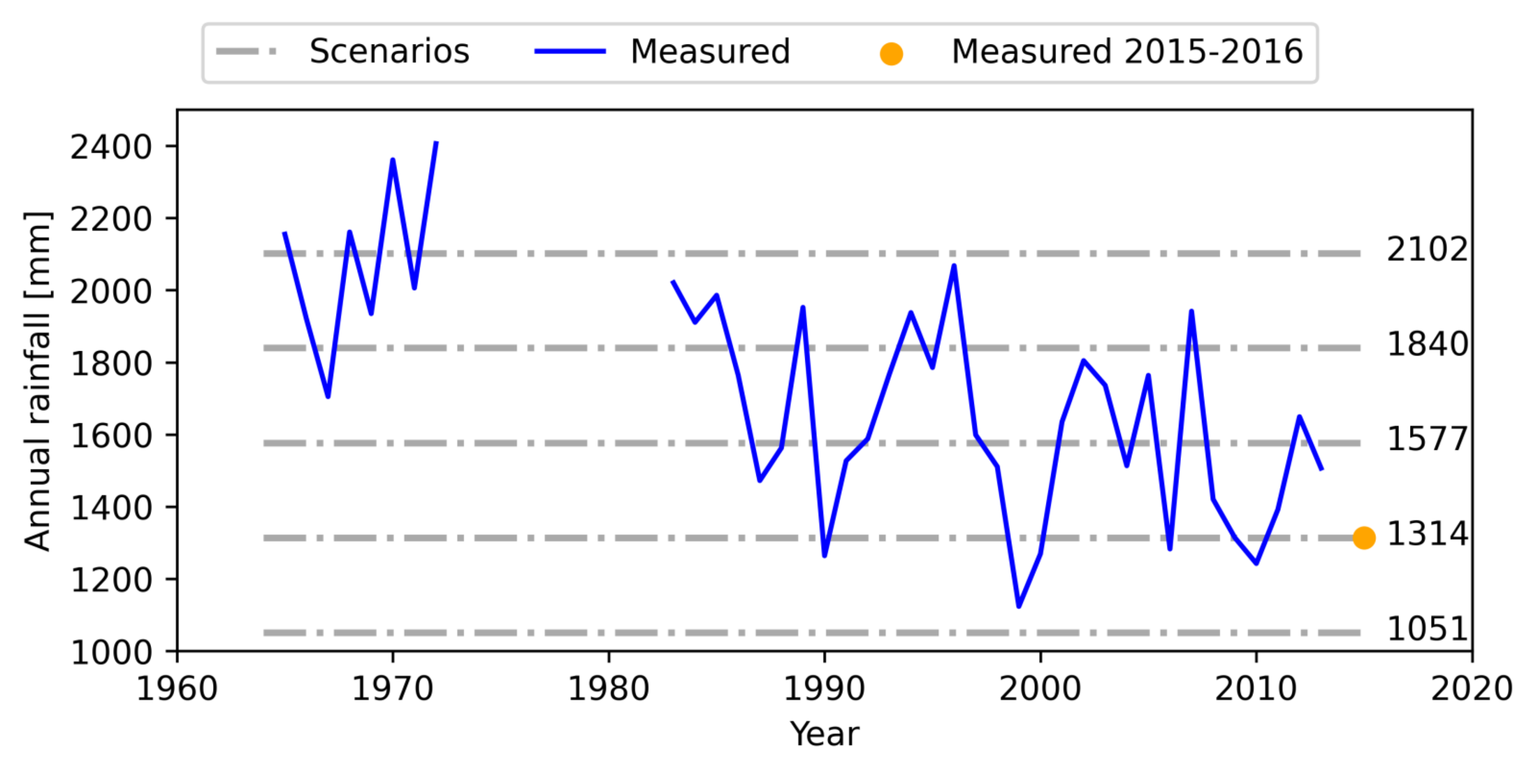
RoGeR Model, Runoff Generation Processes (Steinbrich et al. 2016);

Model input:

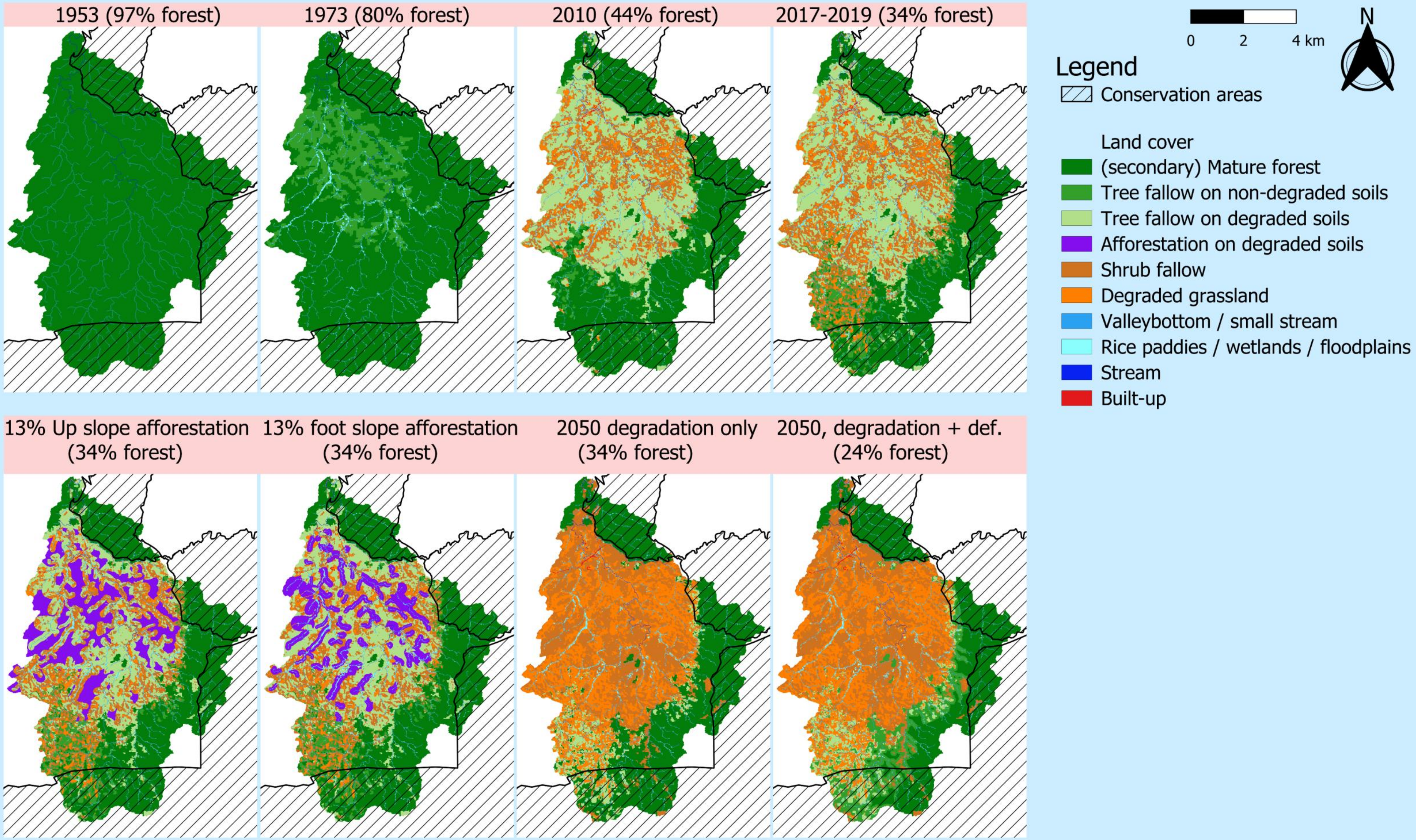
- **DEM** (12x12m TANDEM);
- **Climate** (rainfall, potential evapotranspiration and temperature);
- **Land cover** and **vegetation** parameters;
- **Soil physical parameters** ($K_{sat,}$ porosity, moisture content at field capacity, etc.).
- Parameters based on fieldwork and literature values (Zwartendijk et al. 2020, 2023, in preparation, Ghimire et al. 2017, 2018, van Meerveld et al. 2018, Steinbrich et al. 2016).

Rainfall scenarios

- 10-minute measured rainfall in 2015-2016 1314 mm
- Applying delta-change method to compose rainfall time series with higher or lower rainfall amounts.



Scenario	Factor [-]	Annual rainfall [mm]
Dry	0.8	1051
Measured		1314
Normal	1.2	1577
Wet	1.4	1840
Very wet	1.6	2102



1953 (97% forest)
1973 (80% forest)
2010 (44% forest)
2017-2019 (34% forest)
13% Up slope afforestation (34% forest)
13% foot slope afforestation (34% forest)
2050 degradation only (34% forest)
2050, degradation + def. (24% forest)
0
2
4 km
N
Legend
Conservation areas
Land cover
(secondary) Mature forest
Tree fallow on non-degraded soils
Tree fallow on degraded soils
Afforestation on degraded soils
Shrub fallow
Degraded grassland
Valleybottom / small stream
Rice paddies / wetlands / floodplains
Stream
Built-up

Modelled annual stormflow

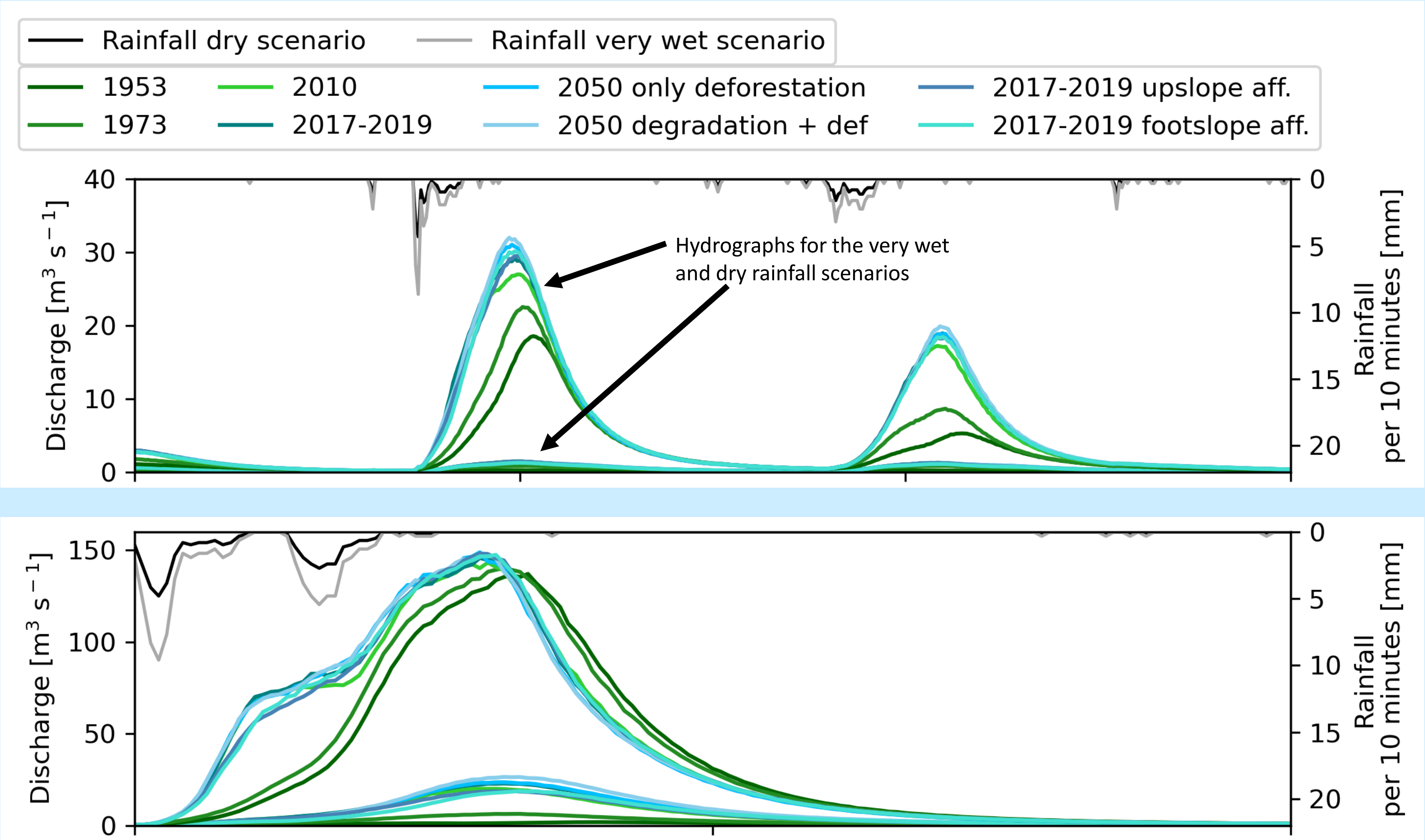
Legend for water balance components

minimum value median value maximum value

Scenario	**Stormflow [mm]**				
1953	12	40	83	139	219
1973	22	55	104	166	250
2010	42	92	162	244	345
2017-2019	45	98	172	258	361
2017-2019 + Up slope aff.	42	92	163	245	347
Foot slope aff.	39	90	161	243	346
2050, only degradation	46	100	175	261	364
2050, deg. + deforest.	49	104	181	270	373

Annual rainfall
1051 mm **2102mm**

Modelled hydrographs



Modelled annual water balance components

Legend for water balance components

minimum value median value maximum value

Scenario	Stormflow [mm]					Actual evapotranspiration [mm]				
1953	12	40	83	139	219	1036	1136	1207	1264	1320
1973	22	55	104	166	250	987	1081	1151	1208	1260
2010	42	92	162	244	345	868	953	1023	1081	1127
2017-2019	45	98	172	258	361	838	919	988	1046	1091
2017-2019 + Up slope aff.	42	92	163	245	347	858	946	1018	1079	1127
Foot slope aff.	39	90	161	243	346	858	946	1018	1078	1126
2050, only degradation	46	100	175	261	364	830	912	981	1039	1083
2050, deg. + deforest.	49	104	181	270	373	801	880	947	1005	1046

Annual rainfall
1051 mm → **2102mm** (Stormflow)

Annual rainfall
1051 mm → **2102mm** (Actual evapotranspiration)

Modelled annual water balance components

Legend for water balance components

minimum value — median value — maximum value

Scenario	Stormflow [mm]					Actual evapotranspiration [mm]					Deep percolation [mm]				
1953	12	40	83	139	219	1036	1136	1207	1264	1320	260	368	487	605	700
1973	22	55	104	166	250	987	1081	1151	1208	1260	268	377	493	607	705
2010	42	92	162	244	345	868	953	1023	1081	1127	288	394	496	599	698
2017-2019	45	98	172	258	361	838	919	988	1046	1091	296	403	503	605	706
2017-2019 + Up slope aff.	42	92	163	245	347	858	946	1018	1079	1127	285	390	489	592	688
Foot slope aff.	39	90	161	243	346	858	946	1018	1078	1126	288	392	492	594	690
2050, only degradation	46	100	175	261	364	830	912	981	1039	1083	301	407	507	610	711
2050, deg. + deforest.	49	104	181	270	373	801	880	947	1005	1046	311	419	518	621	726

Annual rainfall 1051 mm → 2102mm

Annual rainfall 1051 mm → 2102mm

Annual rainfall 1051 mm → 2102mm

Conclusion & outlook (1/2)

- **Rainfall** is the **dominant** factor affecting annual runoff
    - but landcover affects peak flows.
- **Land degradation** at the examined scale had a major effect on stormflow amount and evapotranspiration, but surprisingly **little effect on deep percolation** (dry-season baseflows).
- **Reforesting degraded soils:**
    - **reduces stormflow amounts and groundwater recharge**
    - but also **increases evapotranspiration**.
- Differences in hydrological impacts of reforesting foot-slopes or upslope areas are **negligible** at the meso-scale.
    - **Locally**, foot-slope reforestation **enhances deep percolation** by re-infiltration of overland flow.

Conclusion & outlook (2/2)

- Working on realistic future land cover scenarios with our Malagasy partners

- We expect that coppiced and burned Eucalypt plantations for charcoal production are potentially a larger threat than shifting cultivation because of their deep water uptake and associated potential decrease in deep percolation and dry season flows.

- Long term observations of rainfall and streamflow are needed for sub-catchments to distinguish climatic and land cover effects on hydrological response.

Combining field data and spatially distributed modelling
to understand the effects of land cover, soil degradation, and climate variability on the hydrological response of a meso-scale catchment in Eastern Madagascar

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+ incoming HOF

+ incoming ZA

Rainfall → Infiltration into the soil matrix (Matrix-Inf) → HOF → Replenishment of the usable field capacity (nFK) → Soil saturation and SOF → Deep percolation (TP) → Evapot-ranspiration → Snow accumulation and smowment buckettype → Soil moisture content

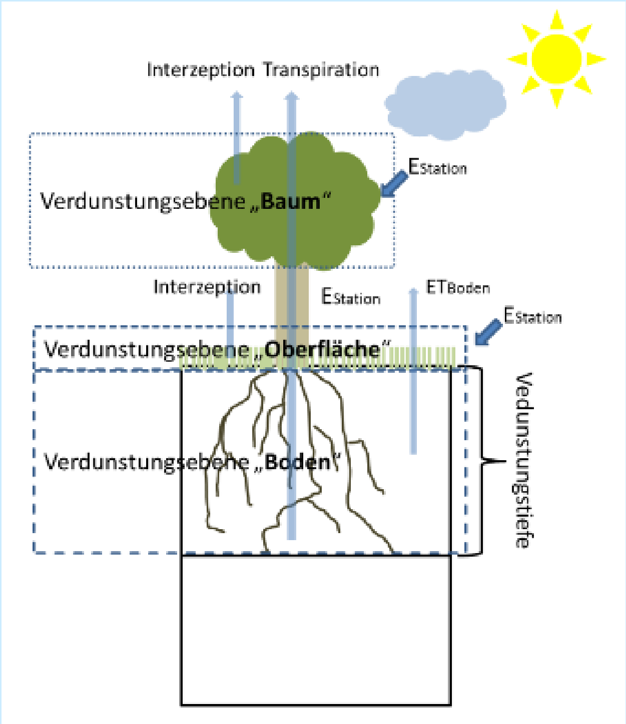
Rainfall
- Interception

HOF
- Infiltration of HOF into macropores into the soil matrix
- Infiltration of HOF through dry cracks into the soil matrix (TR-Inf)
- So if rain exceeds infiltration rate into matrix, remaning water may infiltrate (macropores), remaining water may infiltrate into cracks. the remaining water is HOF minus model output (so infiltration is substracted from HOF before saving HOF value)

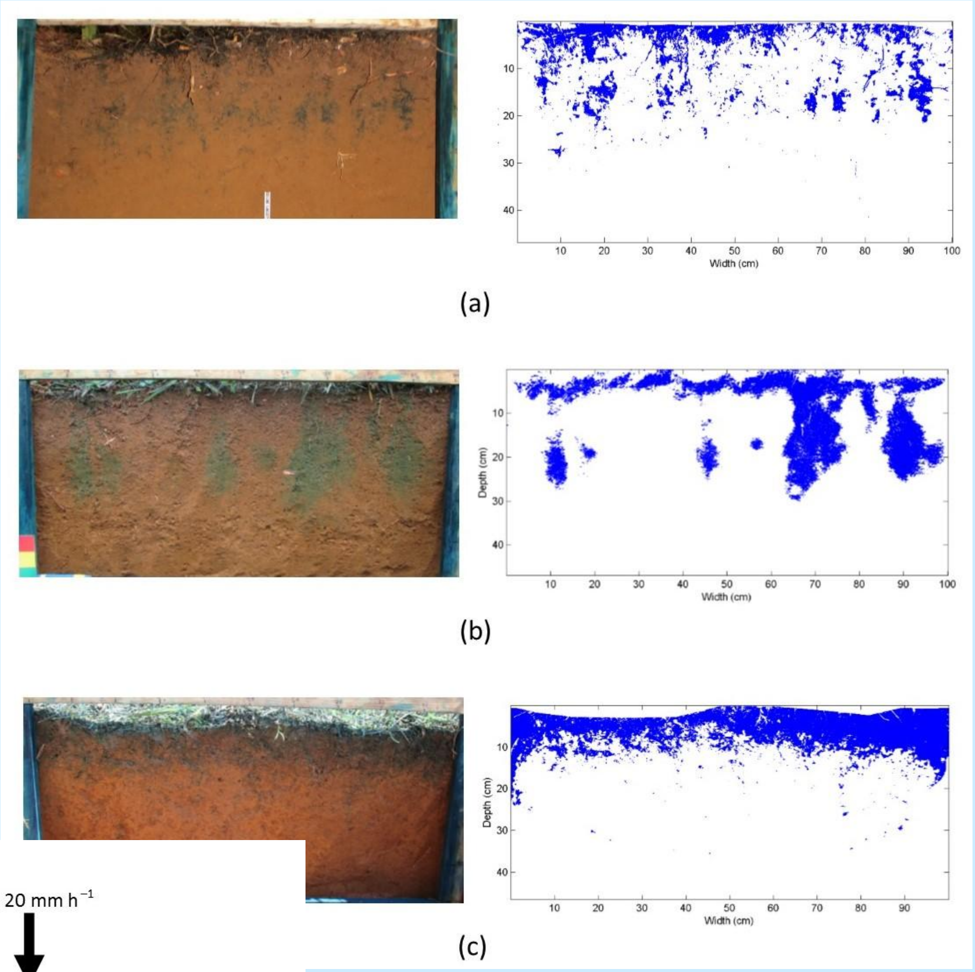
Replenishment of the usable field capacity (nFK)
- Filling the freely drainable pore volume (LK)
- SSSF (in preferential flow paths, MP-ZA)
- Matrix flow, slow intermediate runoff (Matrix-ZA)

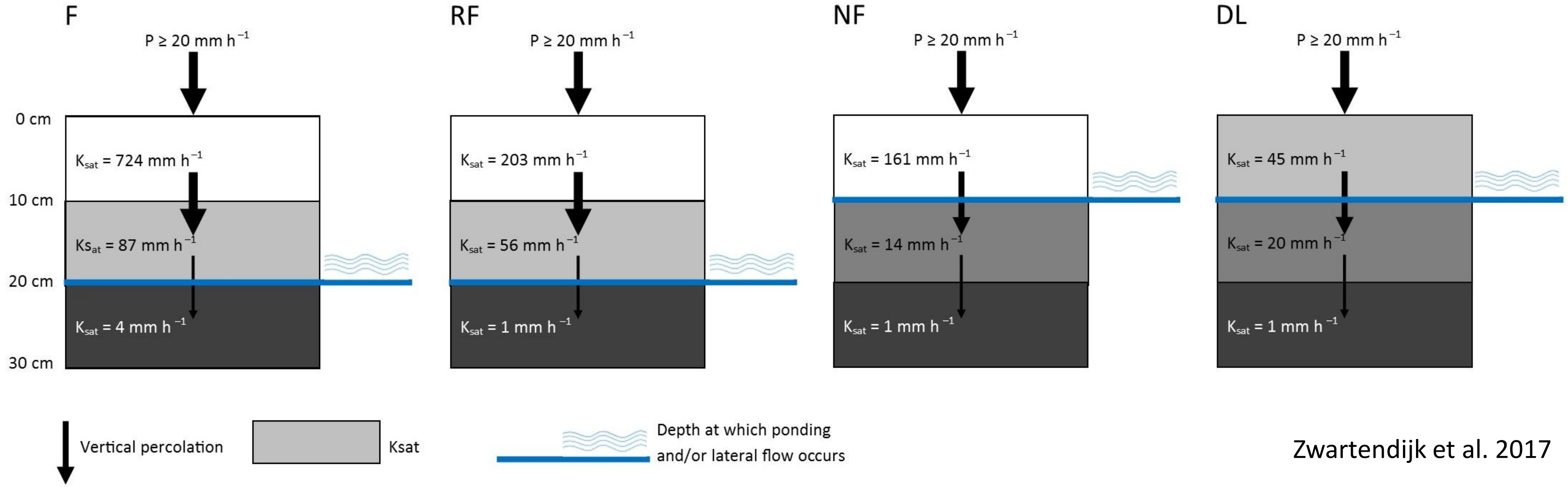
Soil saturation and SOF
- Soil is saturated at the beginning of the time step / soil becomes saturated during timestep

Evapot-ranspiration
- Hourly during rainfall events: evapotranspiration of interception storage
- Daily, no rainfall



Steinbrich et al. 2016





Zwartendijk et al. 2017

Land cover imagery and land cover scenario’s

1. 1953
2. 1973
3. 2010
4. 2017-2019
5. 2017-2019 + Upslope afforestation
6. 2017-2019 + Foot slope afforestation
7. 2050, 2017-2019 + degradation
8. 2050, 2017-2019 + degradation and deforestation

- Forest and forest loss: 1953, 1973, 1990, 2000, 2010, 2015, 2017 (Vieilledent et al. 2018)(30x30m);
- ESA ECCL Land cover 1992-2015 (300x300m);
- ESA Worldcover 2019 (10x10m);
- Estimated deforestation rate of 1.08% per year (Hewson et al. 2018).
- Theoretical afforestation on 20% of deforested areas at first order catchments without remnant forests.

Land cover imagery to land cover scenario's

1. 1953
2. 1973
3. 2010
4. 2017-2019
5. 2017-2019 + Upslope forestation
6. 2017-2019 + Foot slope forestation
7. 2050, 2017-2019 + degradation
8. 2050, 2017-2019 + degradation and deforestation

(secondary) mature forest

tree fallow on non-degraded soils

tree fallow on degraded soils

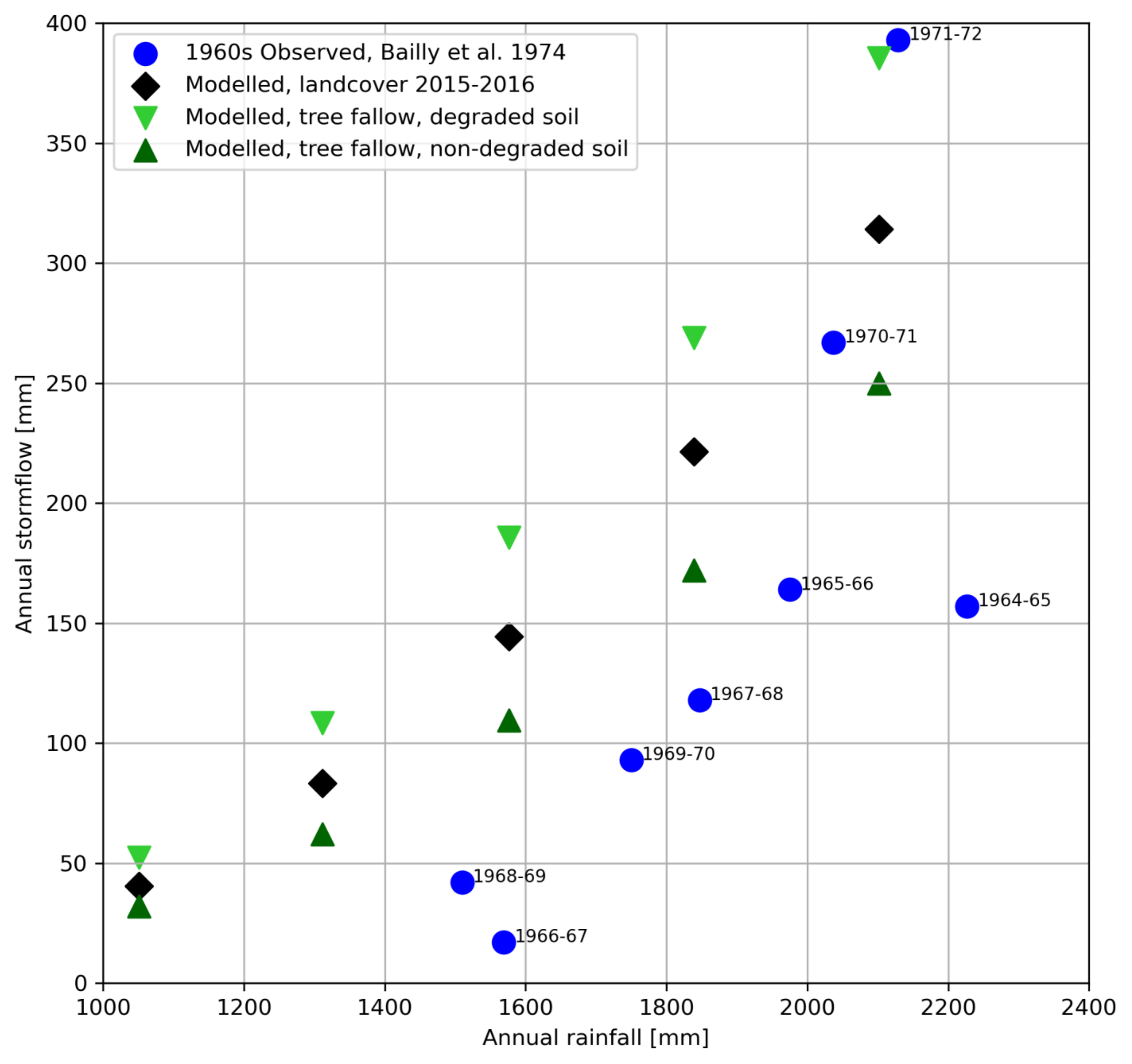
shrub fallow

grass land

Forests on degraded soils

Land cover fractions per scenario

	(secondary) Forest		Tree fallow		**Shrub fallow**	**Degraded grass land**
	Non-degraded soils	degraded soils (afforestation)	non-degraded soils	degraded soils		
1953	97%					
1973	80%		15%			
2010	44%		3%	30%	13%	5%
2017-2020	34%		6%	28%	19%	7%
2017-2020 + Upslope aff.	34%	13%	6%	21%	15%	6%
2017-2020 + Footslope aff.	34%	13%	6%	22%	14%	5%
2050 only degradation	34%		0%	6%	28%	26%
2050 also deforestation	24%		10%	6%	28%	26%



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