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Dominant drivers of runoff in a slash-and-burn affected catchment in upland Eastern Madagascar

- Hillside runoff response is dominated by saturation-excess overland flow
- Strong threshold behaviour in terms of the antecedent soil moisture storage in the upper 30 cm of the soil plus event total rainfall amount
- Increased hydrological connectivity between hillslopes and valley bottom under wetter conditions

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Introduction: Slash and burn

- Slash-and-burn agriculture dominates large areas in the tropics. This results in a mosaic of land uses.
- Repeated burning decreases soil biodiversity, soil organic carbon content, rooting depth and density as well as the infiltration capacity.
- This can result in increased overland flow and erosion, and reduced groundwater recharge and dry-season streamflow.
- However, the interception and transpiration losses are also lower for the young vegetation.
- Few studies have focused on the runoff response in highly heterogeneous catchments that have undergone slash and burn agriculture for several decades.



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Research goals

The objectives were to:

1. Examine the responsive characteristics of the mainstream of the catchment;
2. Relate these responses to antecedent wetness and rainfall characteristics;
3. Examine the contribution of the responsive areas of connected wetlands and streams vs contribution of hillslope to streamflow responses.

Hypotheses:



- Discharge amount and time related parameters depend on the previous wetness of the catchment and rainfall amount, the response being threshold dependent;
- Streamflow response is majorly affected by the patchy land use, in combination with the present wetlands and rice paddies delaying flow.



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Study area

- >40% of Madagascar's forest cover was lost in the past 60 years, largely due to smallholder slash-and-burn agriculture (Harper et al., 2007);
- The research area, the Ankeniheny Zahamena Corridor, is a biodiverse area on the Eastern escarpment of Madagascar where various conservation interventions aim to reduce forest clearance and to promote active reforestation (Portela et al., 2012);



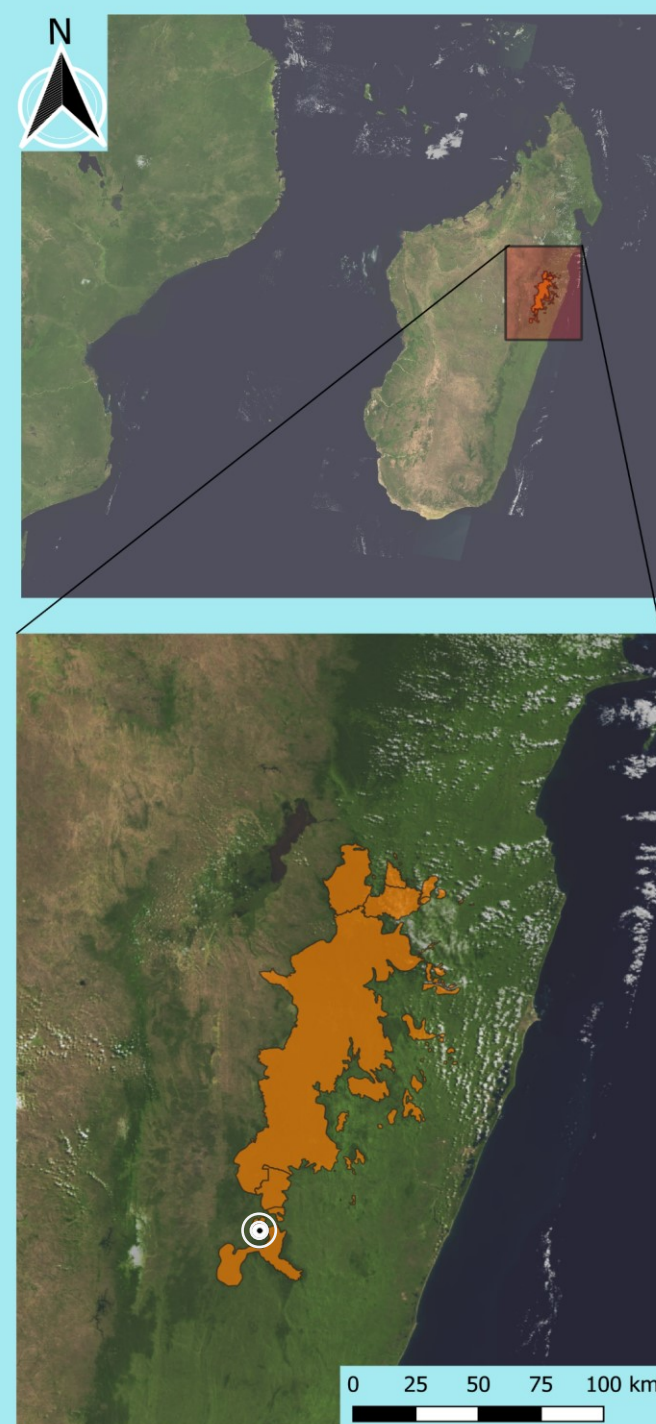
- Within the research area forest cover decreased by 15% from 1992 to 2015;



- The climate is seasonal with 75% of the annual rainfall falling in the rainy season (November-April) ;



- Soils classified as tropodults.



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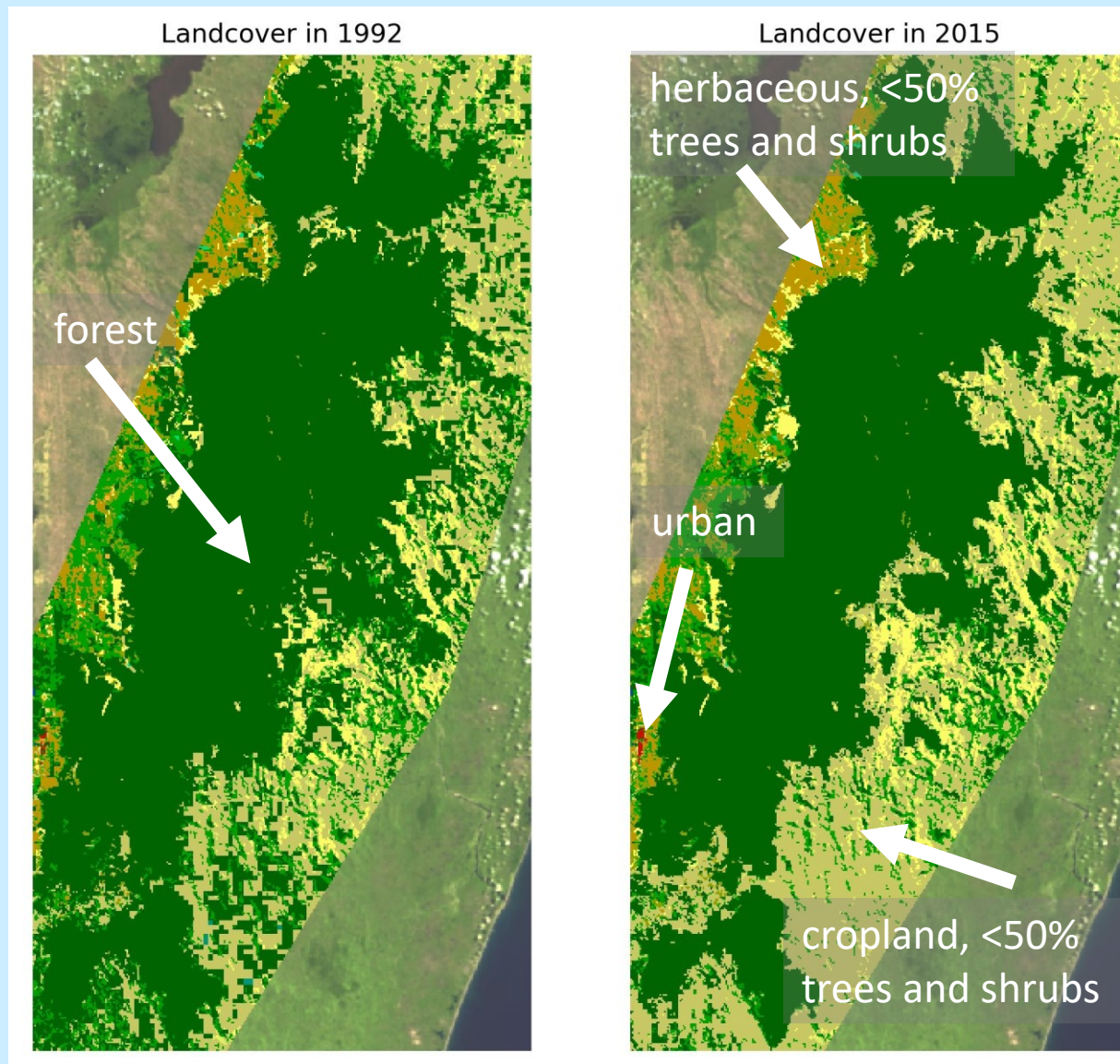
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Land cover change in Corridor Ankeniheny Zahamena

Land cover (%)	1992	2015
Forest	44	37
Shrub and tree fallow	10	9
Grass and herbaceous	12	18
Other	34	36



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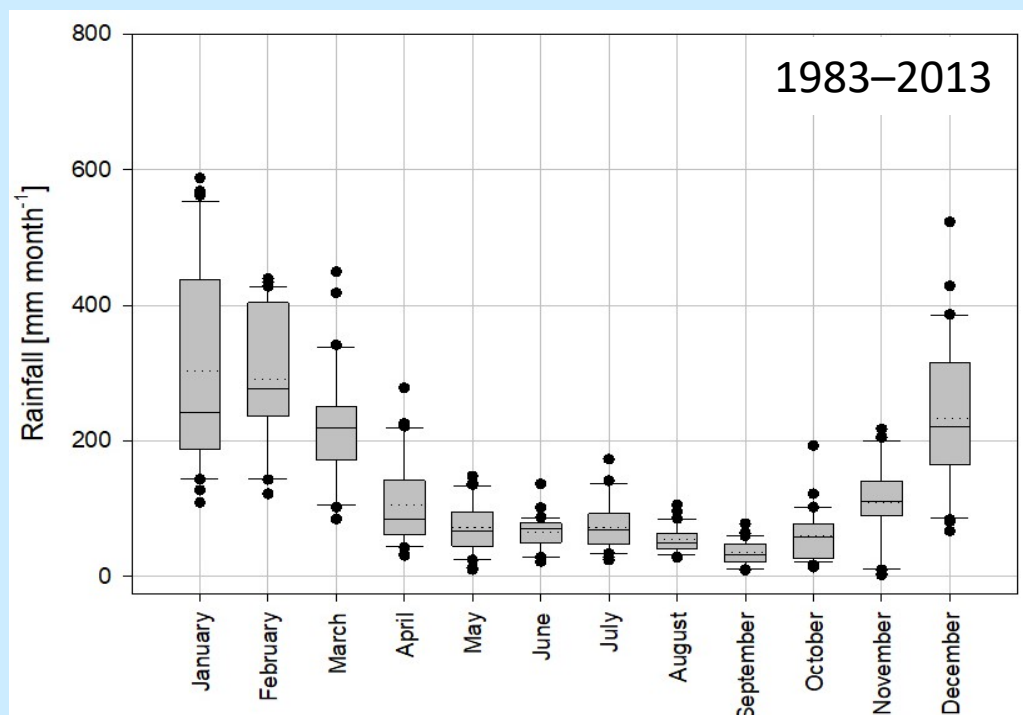
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Climate and variability in monthly rainfall

- Mean annual rainfall at Andasibe (5 km from the catchment, at 990 m a.s.l.) was 1625 mm yr⁻¹ for the 1983–2013 period;
- Monthly rainfall totals between December and March exceed 200 mm on average and are <100 mm between April and October;
- The average temperature was 15°C during the dry season (April to October 2015) and 22°C during the wet season (November to March, 2014-2015) (Ghimire et al., 2017).



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Study catchment

- The Marolaona catchment 31.7 ha is located at an elevation of 940–1000 m a.s.l. and was first deforested more than 75 years ago;
- The catchment was monitored between 1963 and 1972 (Bailly et al. 1974);
- Since 1972 slash-and-burn agriculture took place with fallow periods and plot sizes depending on the ownership;
- Land use is very patchy, dominated by tree fallows (<15 years old), shrub fallows (<5 years old), and annually coppiced and burned eucalypt plantations (for charcoal production);
- We re-instrumented the catchment in 2015.

Legend

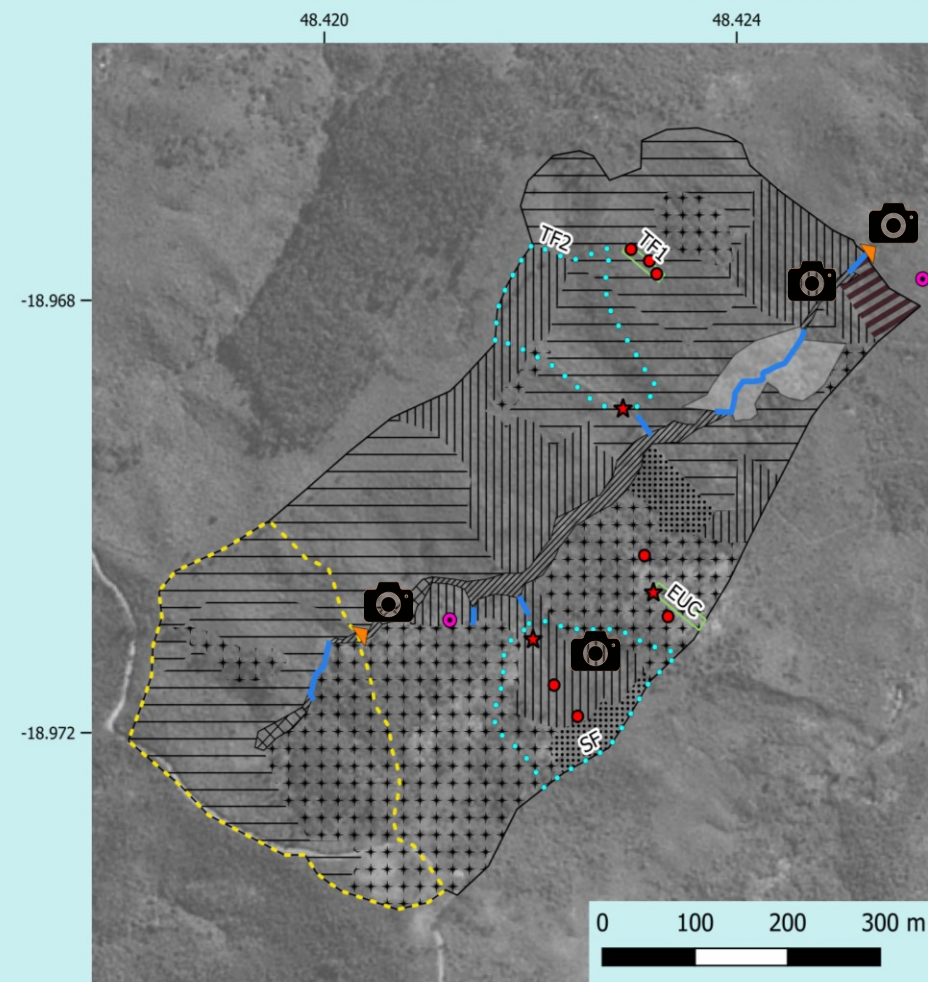
- • • 0-order catchment
- Overland flow plot
- - - Sub-catchment

Measurements

- Rain gauge
- Weir
- Fully screened well
- ★ Soil moisture sensors and fully screened well

Land use

- 0.3 ha (1%) Active Agriculture
- 9.4 ha (30%) Eucalyptus
- 0.8 ha (2%) Degraded (grass)land
- 0.8 ha (2%) Secondary forest
- 5.9 ha (19%) Shrub fallow
- 13.7 ha (43%) Tree fallow
- 0.2 ha (1%) Rice paddies (156 m, 17% of thalweg)
- 0.7 ha (2%) Wetlands (533 m, 58% of thalweg)
- Stream (230 m, 25% of thalweg)



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Geology & soils (1/3)

- The hillslopes are:
 - moderate to steep: 10 to 50° (average: 21°);
 - relatively short (60–300 m);
 - generally convexo-concave.
- The soils:
 - are classified as tropudults;
 - are at least 6 m deep based on four separate augerings (Zwartendijk et al. 2020a);
 - vary in texture between sandy clay loam and clay (up to 45% clay at the surface, increasing slightly at a depth of 60–70 cm; Andriamananjara et al., 2016).
- The bedrock consists of Precambrian metamorphic and igneous basement rocks: migmatites and granites (Bailly et al., 1974; Du Puy and Moat, 1996).



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Geology & soils (2/3)



- The infiltration capacity of the soil decreases with depth, with median values for measurements within the catchment of:
 - 0-10 cm: 500 mm hr⁻¹
 - 10-20 cm: 20 mm hr⁻¹
 - 20-30 cm: 1.6 mm hr⁻¹
- The infiltration capacity of the soil also varies between land uses:
 - highest for eucalypt and tree fallow;
 - lowest for degraded grasslands.
- These results (Zwartendijk et al. 2020a) are in line with measurements elsewhere in the research area (Zwartendijk et al. 2017).



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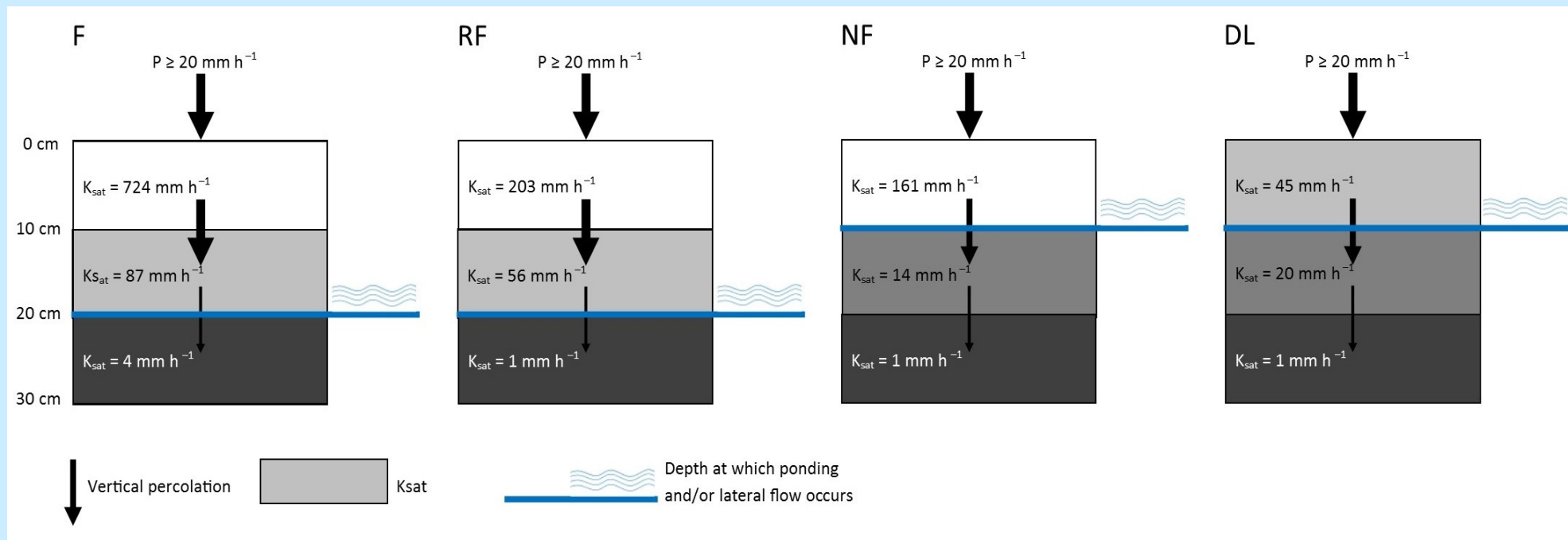
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Geology & soils

(3/3)



Zwartendijk et al. (2017):

- The decline in K_{sat} by one to two orders of magnitude between the soil surface and 30 cm depth;
- K_{sat} at the soil surface highest for forest (median 724 mm h^{-1}) and lowest for degraded grasslands (median 45 mm h^{-1});
- Median K_{sat} of 1 mm h^{-1} for land uses other different than forest;
- For rainfall intensities $\geq 20 \text{ mm h}^{-1}$ a perched water level will develop between 10 and 20 cm below the soil surface.

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Instrumentation

- Rainfall and discharge at two locations in the catchment;
- Soil moisture sensors and fully screened wells (Zwartendijk et al. 2020a) and overland flow measurements at four plots;
- Water sampling for four events ($\delta^{18}\text{O}$).

Legend

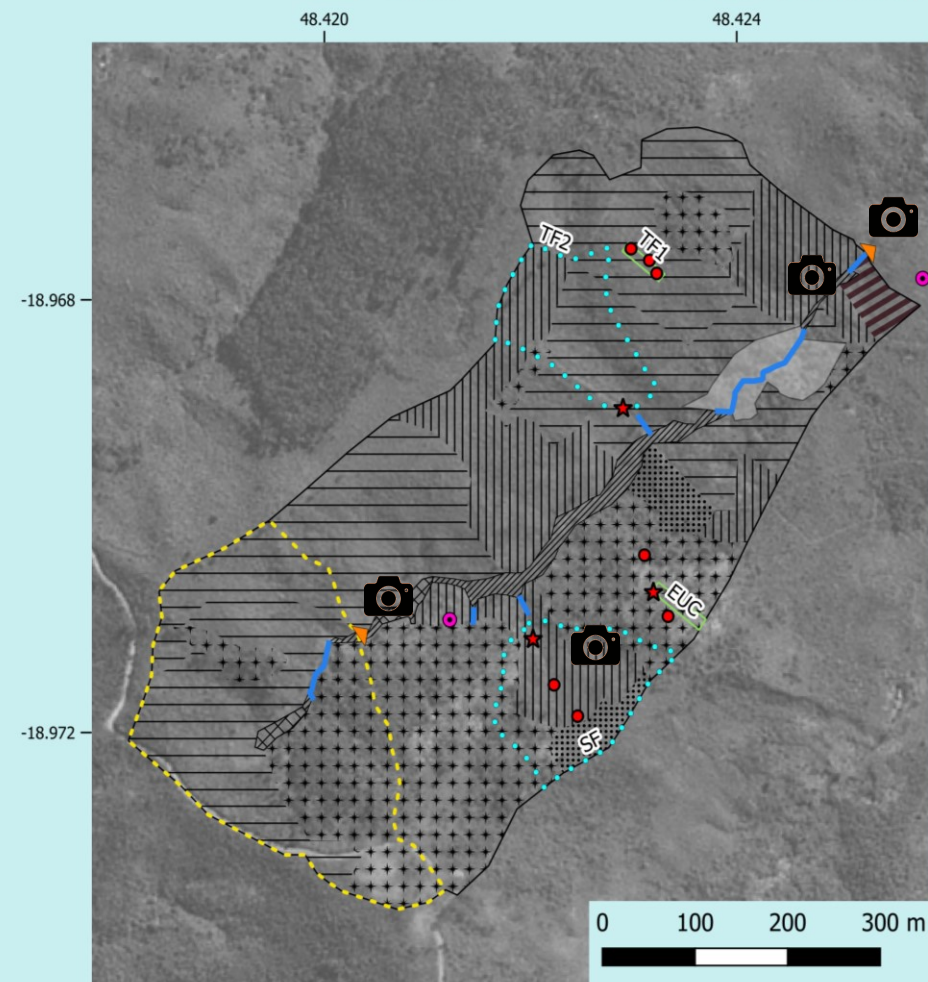
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- Weir
- Fully screened well
- Soil moisture sensors and fully screened well

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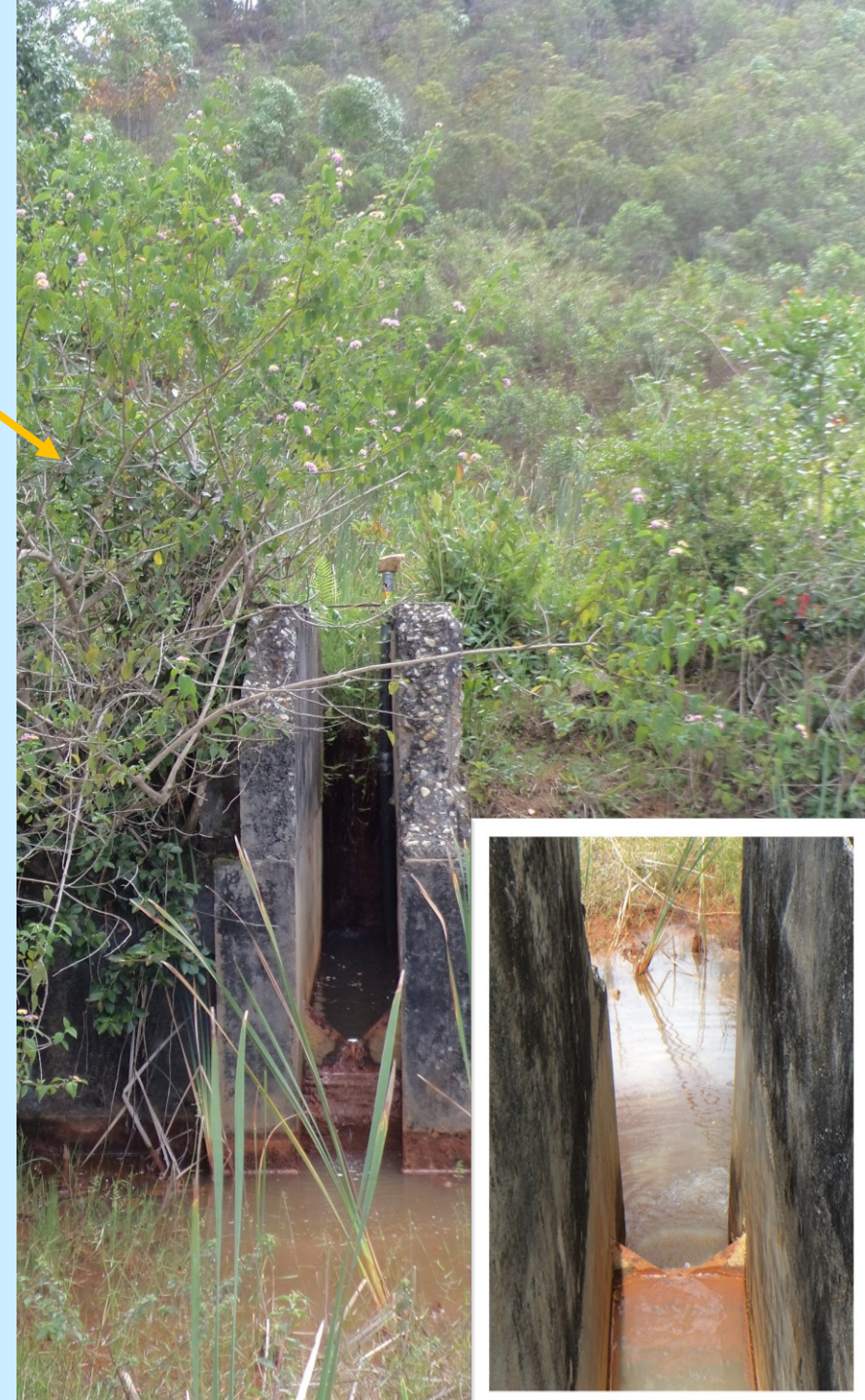


Photos of the catchment (1/2)

Downstream weir



Upstream weir



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Photos of the catchment (2/2)

Rice paddies (and wetland in background)
50 m upstream of downstream weir

South-East side of catchment (SF plot,
photo taken from North-West side)



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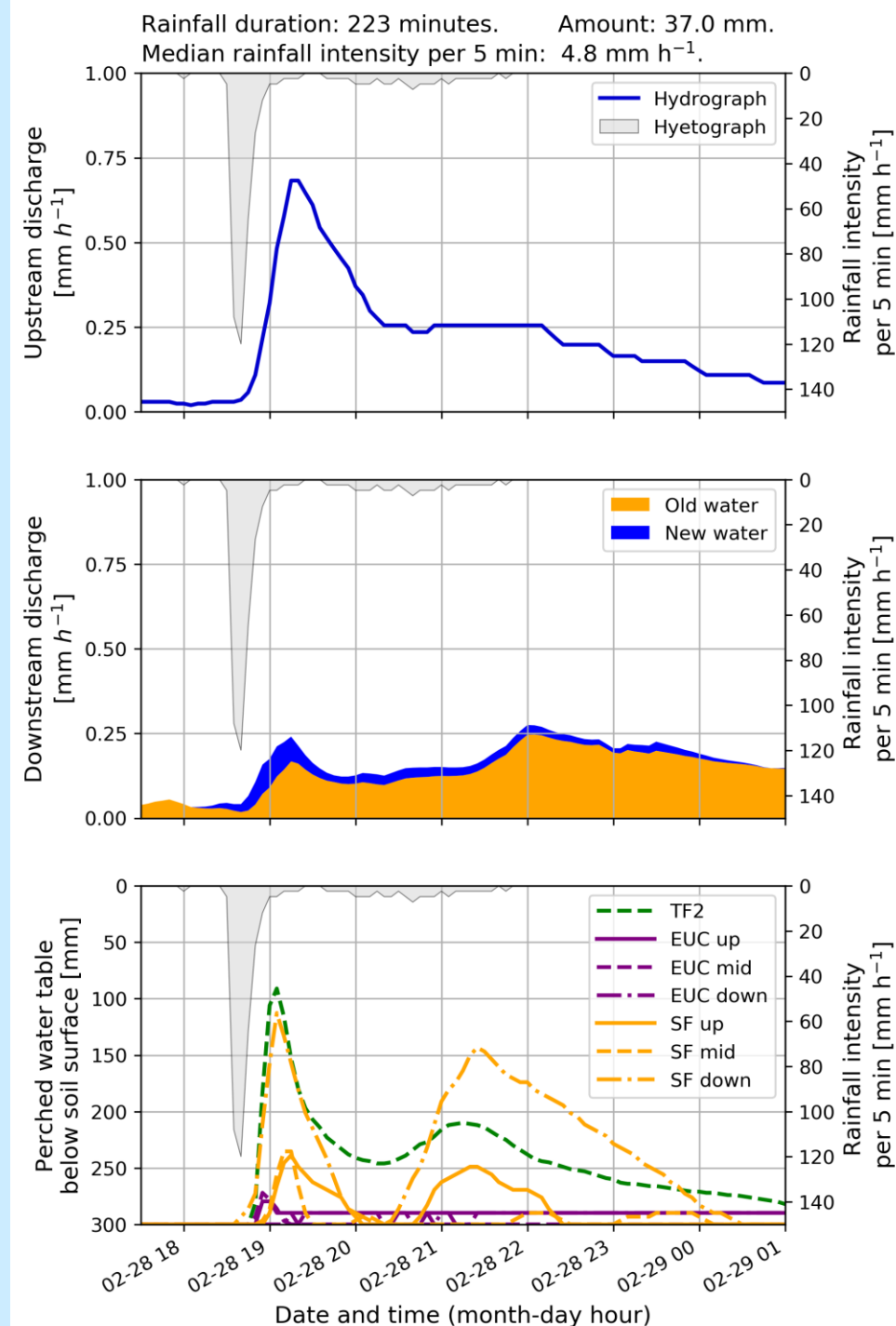
Summary & perspective



Responses (1/3)

- A typical rainfall response (shown in figure)
 - When the maximum 5-minute rainfall intensity is larger than the median K_{sat} at 10-20 cm depth ($\sim 20 \text{ mm h}^{-1}$), soil saturation and perched water levels develop;
 - Water levels rise to 70 mm from the soil surface;
 - Leading to a first peak in downstream discharge (in this figure 0.24 mm hr^{-1});
 - There is a rapid decline of all catchment responses after the first peak.
- In case rainfall continues with a lower intensity and the catchment is wet (in this example $< 8 \text{ mm hr}^{-1}$), there is a second peak with a longer duration.
- More timeseries can be found [here](#).

TF2=Tree fallow EUC=Eucalyptus SF= shrub fallow

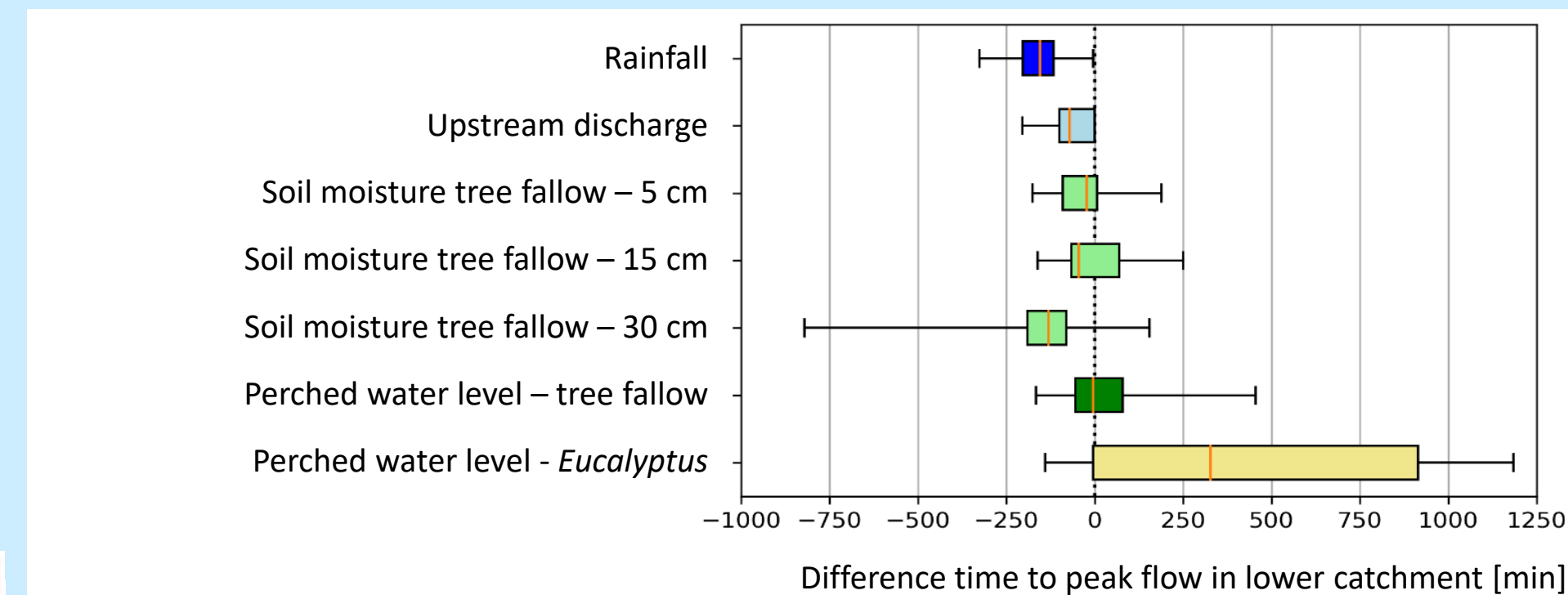




Responses

(2/3)

- The peak response within the catchment occurred before the peak in downstream discharge;
- Lag-to-peak and lag-to-centroid are also smaller for the upstream gauge than for downstream;
- Median storm flow durations are shorter for the upstream gauge than downstream;
- Median peak-flows larger for the downstream gauge than for upstream.



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Responses

(3/3)



- Wetlands and rice paddies occupy **3%** of the catchment area (75% of the stream and riparian area);
- Median runoff ratio (i.e., minimum contributing area): **4%**
- Maximum storm and peak-flow larger for upstream than for downstream gauge.



	Upstream (n=34)		Downstream (n=27)	
	Median	Min-max	Median	Min-max
Peak flow [mm h⁻¹]	0.21	0.02-4.64	0.39	0.13-3.92
Storm flow [mm]	0.37	0.03-12.7	1.10	0.04-9.70
Minimum contributing area [%]	3.50	0.30-22.0	4.10	0.70-50.0

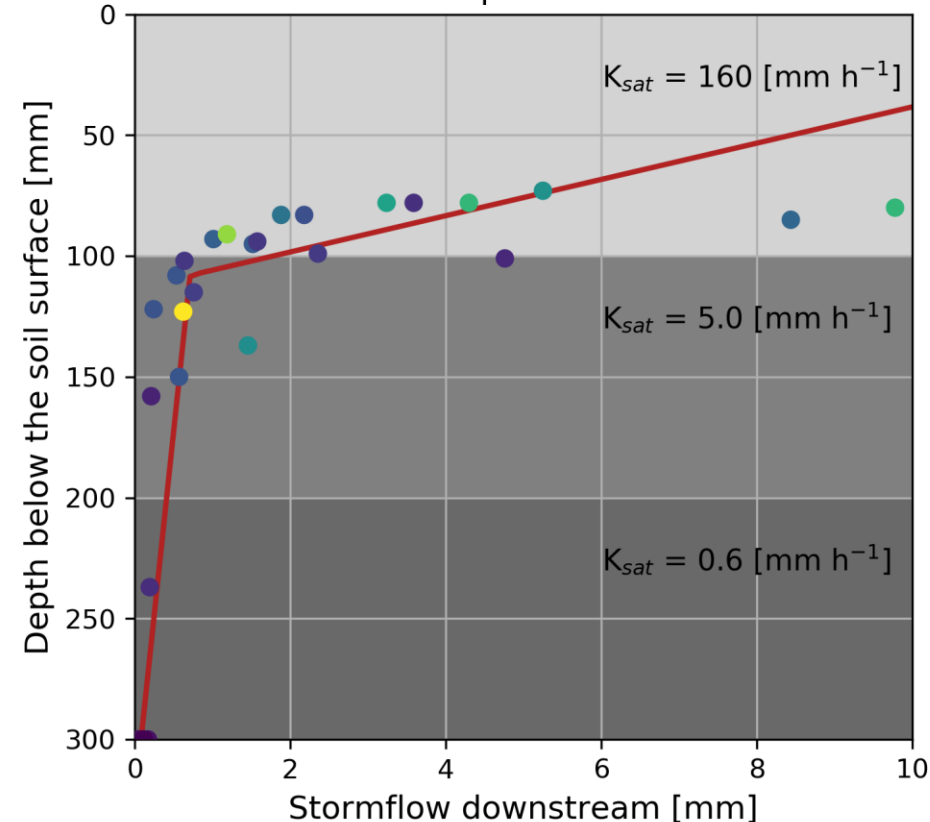
Correlations & thresholds

(1/2)

- Thresholds for storm amount (and peak flow) determined for ASI+P* are similar as thresholds for overland flow occurrence;
- Threshold relation between maximum perched water levels and storm (and peak) flow amount:
 - The threshold corresponds with water level increasing in higher K_{sat} layer of the topsoil.
- Strong correlations between stormflow and peak flow amount ($r_s \geq 0.77$);
- Storm flow amount and minimum contributing area are well correlated to rainfall event duration for downstream, but not for upstream.

*ASI+P = Antecedent soil moisture index (over the top 30 cm) + event rainfall amount (at TF2).

Relation between maximum perched waterlevel and stormflow



Maximum hourly rainfall intensity [mm h⁻¹]



— Regression line, piecewise ($p=0.0$)

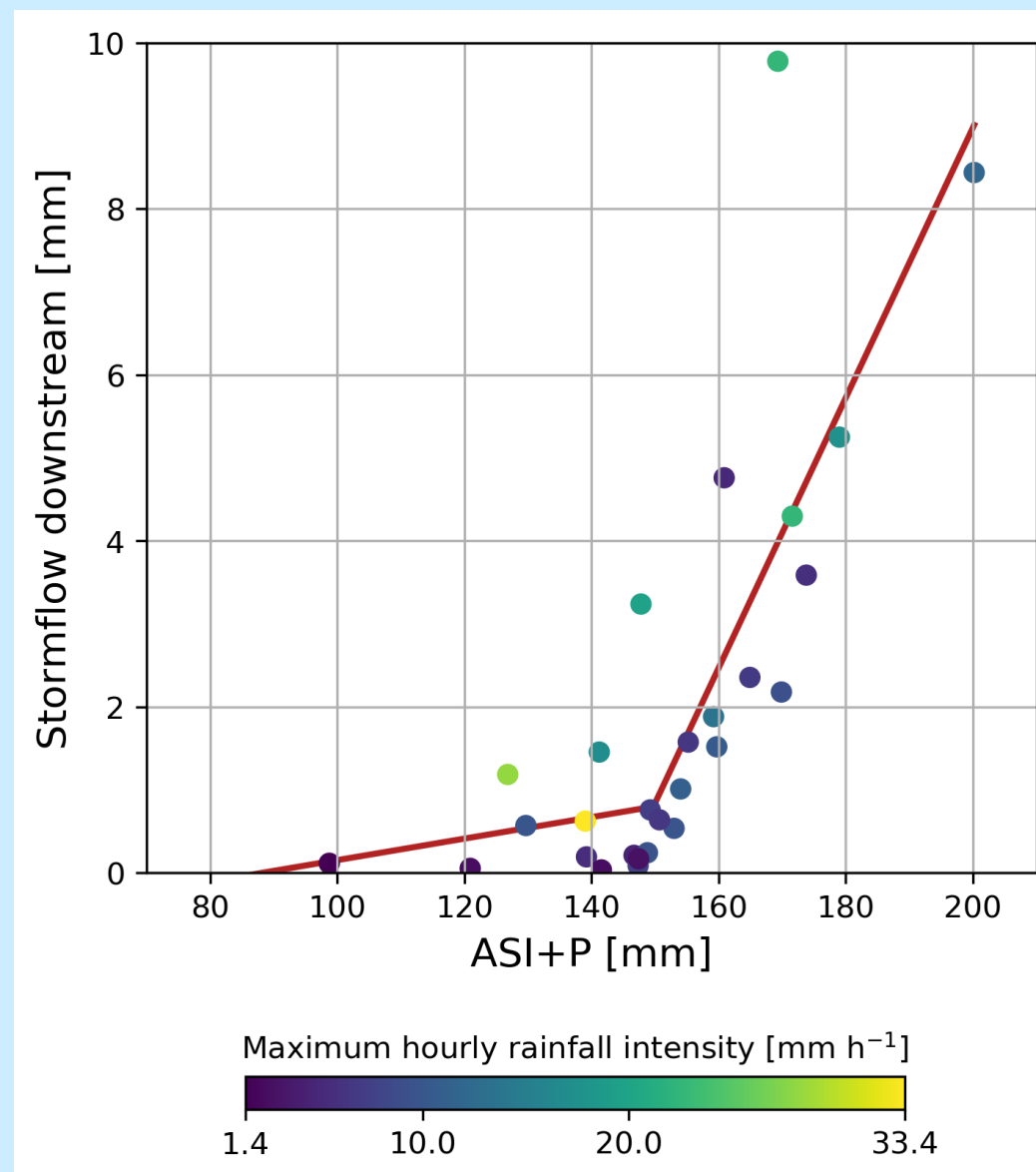
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Correlations & thresholds

(2/2)

ASI+P thresholds for storm (and peak flow) are similar to the thresholds for overland flow occurrence.

ASI + P threshold [mm]	TF2	EUC
Overland flow break	137	87
Stormflow break	150	99



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Conceptual model

- **Small rainfall event** and/or dry antecedent conditions:



- Only rainfall on stream, wetlands and rice paddies reaches catchment outlet as event water;
- None to minor perched water tables on the hillslopes.

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

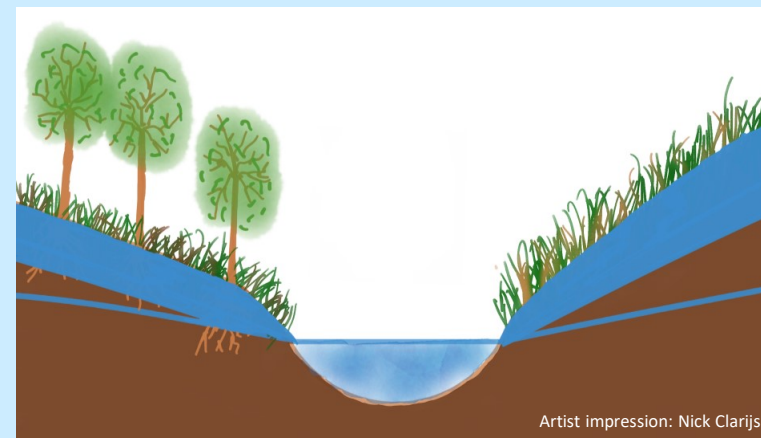
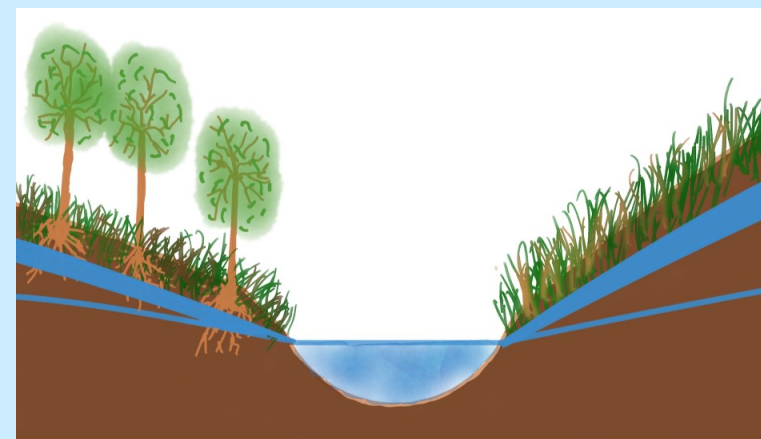
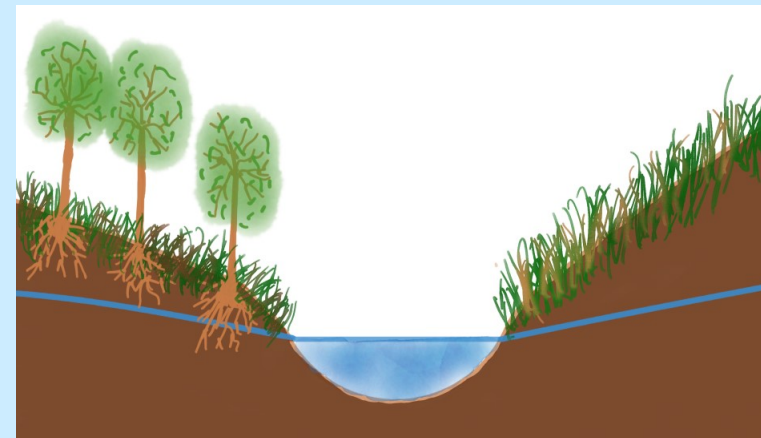


- Some perched water tables on the hillslopes;
- Saturation excess overland flow at degraded sites and in the riparian zone;
- Stream flow dominated by pre-event water.

- **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.



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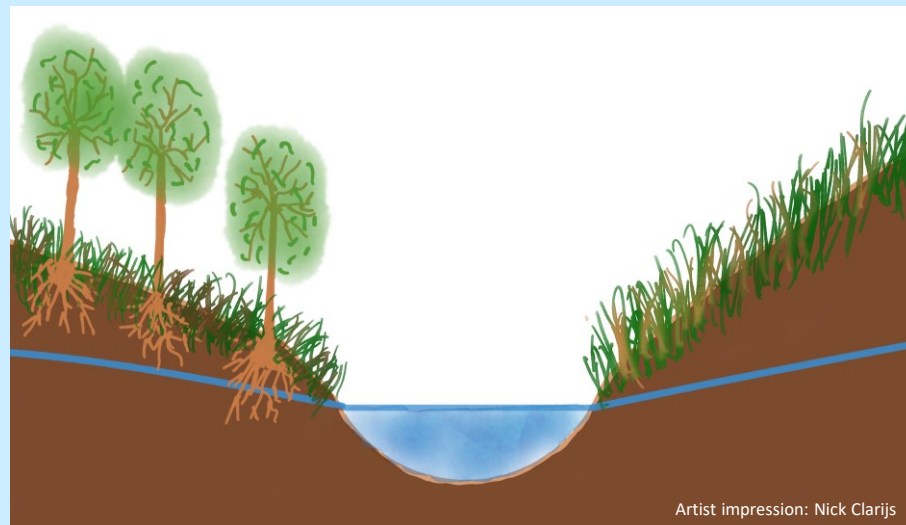
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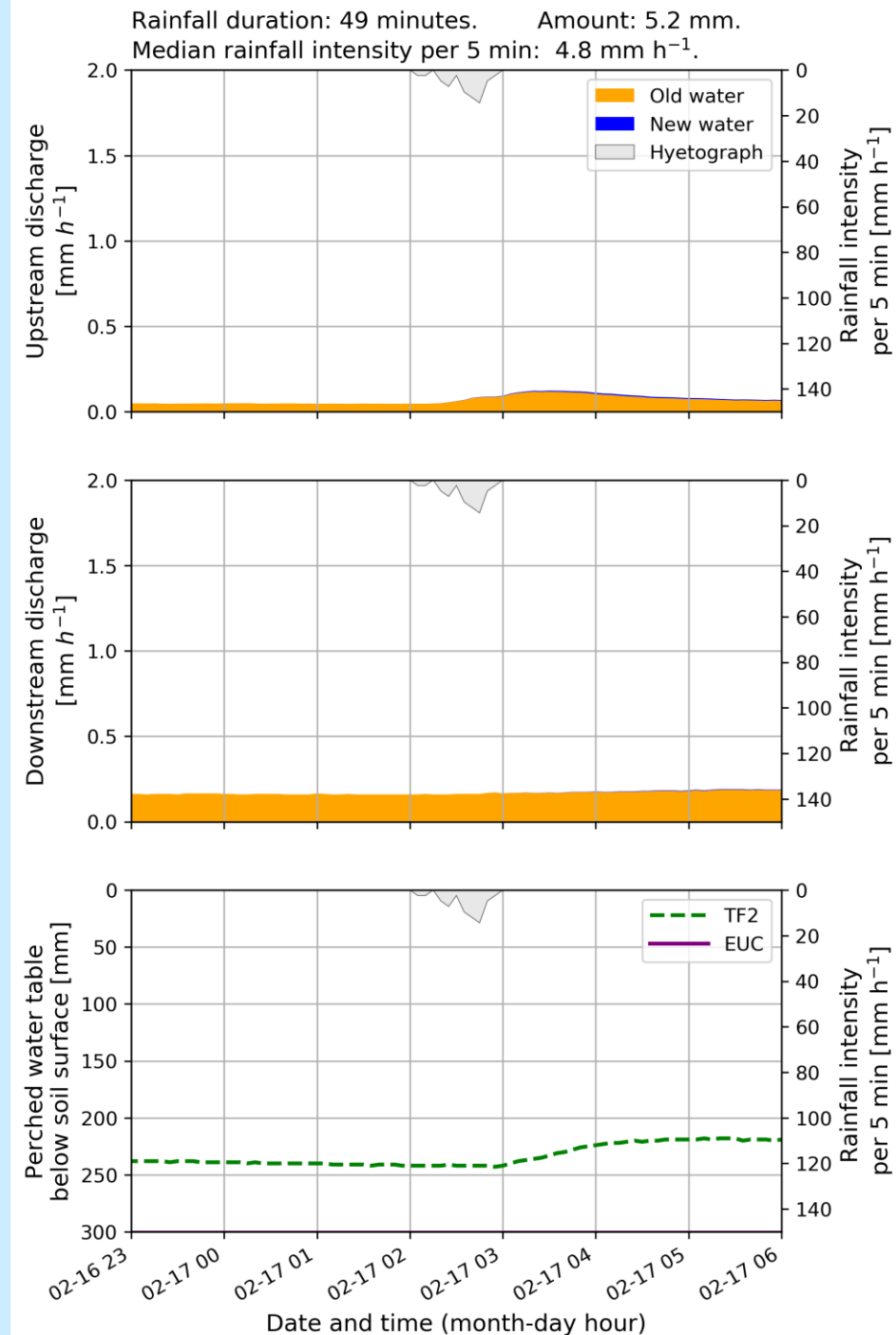


Conceptual model

- **Small rainfall event** and/or dry antecedent conditions:
 - Only rainfall on stream, wetlands and rice paddies reaches catchment outlet as event water;
 - None to minor perched water tables on the hillslopes.



Artist impression: Nick Clarijs



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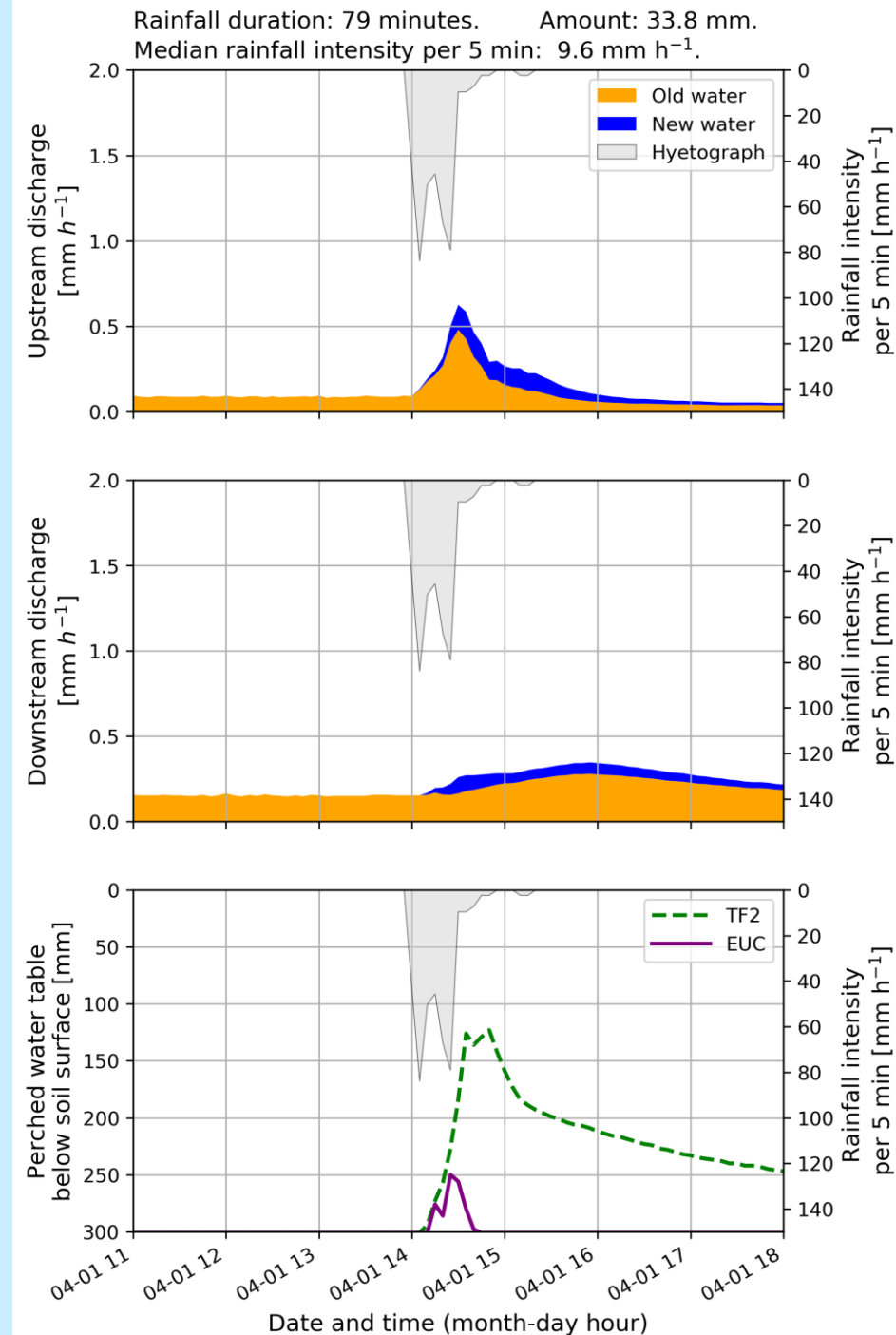
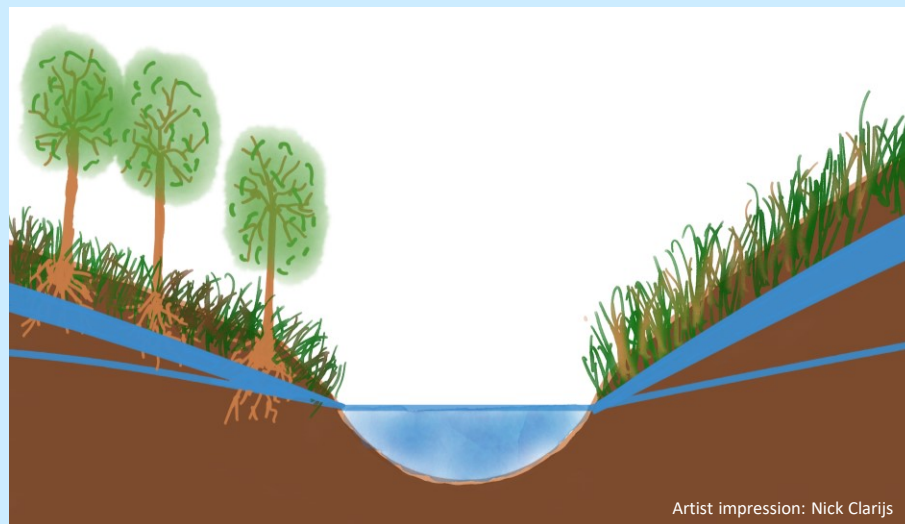
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Conceptual model

- **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 near the riparian zone;
 - Stream flow dominated by pre-event water.



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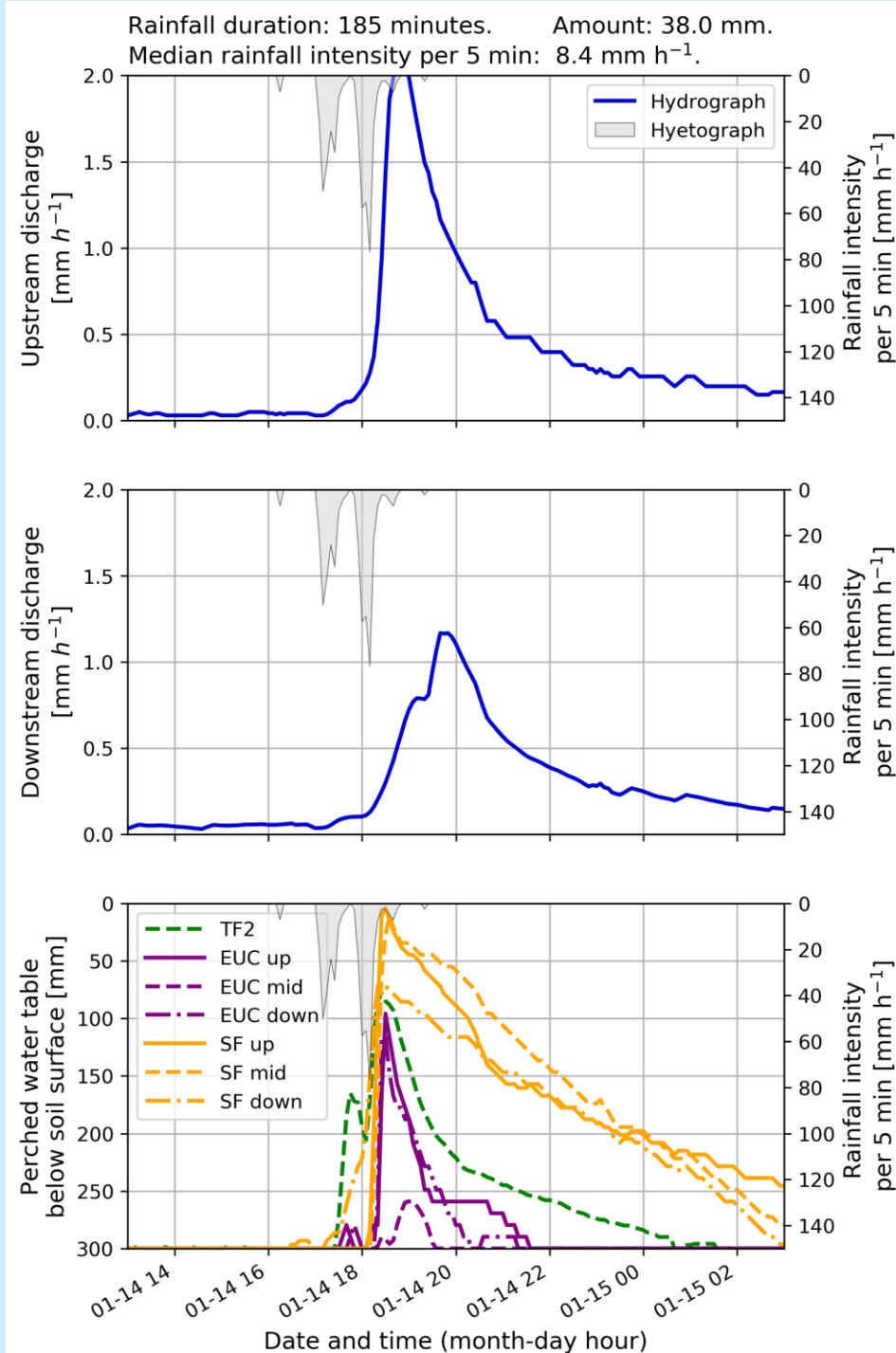
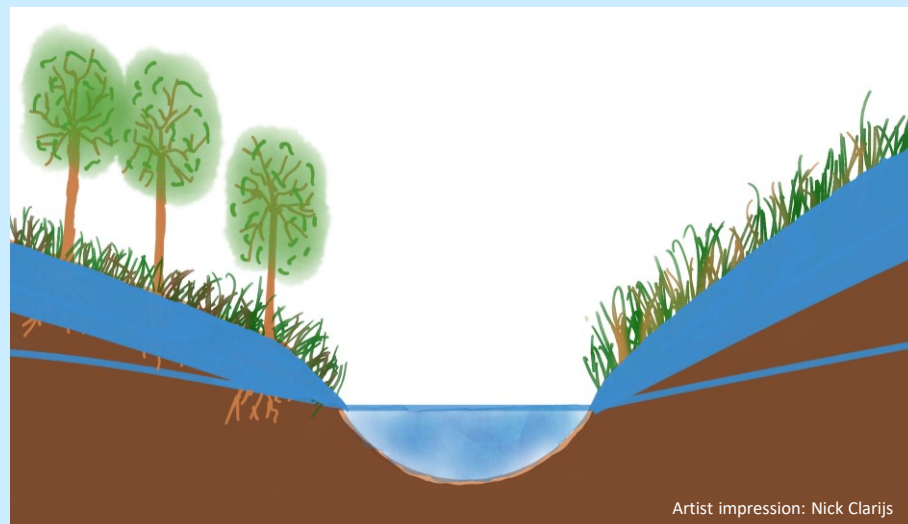
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Conceptual model

- **Very large rainfall event** and/or wet antecedent conditions:
 - A large part to catchment is hydrologically connected to stream via perched water tables;
 - Saturation excess overland flow also from upslope areas;
 - Event-water dominates stream flow.



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Summary and perspective

- The results indicate:
 - Large streamflow response after soil moisture plus rainfall thresholds;
 - Increased hydrological connectivity between hillslopes and valley bottom with increased wetness of the catchment;
 - Event runoff is dominated by pre-event water;
 - Soil saturation (perched water tables) up to ridge of the catchment;
 - Large differences between upstream and downstream discharge.
- These results will be used to validate a hydrological model to determine the net effect of concurrent changes in land use change on stormflow totals and the seasonal flow regime.



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