Hydrodynamic modelling of a cultivated hillslope under sudanian climate (North Benin)

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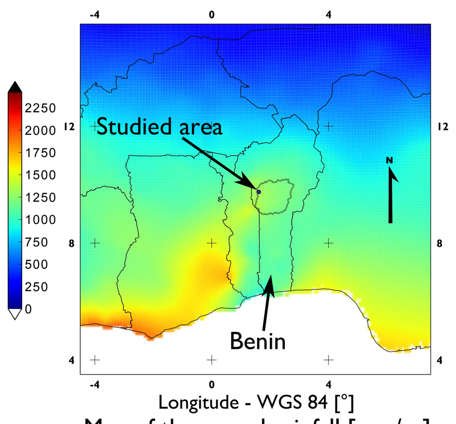
CONTEXT

Sudanian climate area

The study is located in a Sudanian climate area which is characterized by a 1200 mm annual rainfall with two peaks of precipitation. West-African monsoon annual regulation could be linked to the remaining soil water at the end of the dry season in the Sudanese region [Philippon and Fontaine, 2002].



Map of the annual rainfall [mm/yr]

Soil-atmosphere interactions

The Actual Evapotranspiration (AET) of the Ara catchment (12 km²) in 2006 is estimated to be around 80 % of the annual rainfall [Guyot et al., 2009]. If a 1D Soil-Vegetation-Atmosphere Transfer (SVAT) model is used to simulate vertical hydric fluxes, the simulated groundwater dynamics is inconsistent with the observed one. The missing process of the 1D approach should be the lack of groundwater distribution at the hillslope scale.

OBJECTIVES

Objectives

- Reproduce water storages and fluxes at the soil-atmosphere interface
- Enhance the understanding of hydrological processes at the hillslope scale

Question

Is a 2D vertical model able to simulate the hillslope hydrodynamics ?

Methods

- Performing a hydrodynamic model of a well-instrumented cultivated hillslope
- Testing different hillslope configurations and hydrological assumptions
- Comparing the observed and simulated water fluxes

MODELLING TOOLS

Hydrus 2D software

Hydrus 2D software solves the Richards Equation with computational finite element model. The water uptake by the plant roots is incorporated by a sink term in the flow equation. We use the van Genuchten - Mualem hydraulic model without hysteresis and the "S-shaped" root water uptake reduction model.

ET_0 partitioning [Ritchie, 1972]

$$T_p = ET_0 \left(-0,21 + 0,70.LAI^{1/2}\right) \quad \text{with} \quad 0,1 < LAI < 2,7$$

Tp: potential transpiration

ET_0: reference evapotranspiration

Leaf Area Index (LAI)

The hillslope LAI is the average of the LAI of cultivated area and tree weighted by their relative surface.

MATERIAL

Hillslope characteristics

- Mean elevation (AMSL): 436 m
- Difference in level: 20 m
- Length: 560 m
- Land use: cultivated area
- Pedology and geology: "Ferruginous tropical leached" type soils weathered gneiss and micaschist, fractured bedrock substratum

Input data

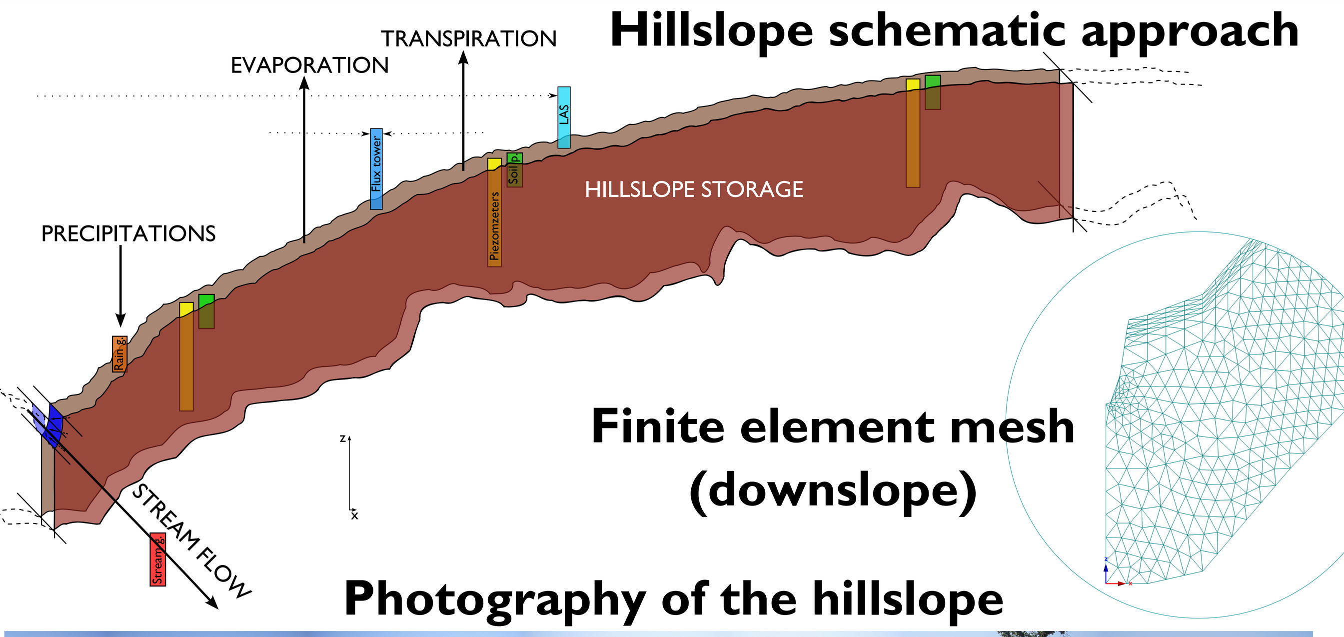
- Precipitation:
  1 rain gauge
- Potential Evapotranspiration:
  1 meteorological station

External data used for comparison

- Suction and Water content:
  3 monitored soil profiles of 2 m deep
- Actual Evapotranspiration:
  1 Large Aperture Scintillometer (LAS),
  1 Flux tower
- Groundwater level:
  9 piezometers
- Streamflow:
  1 stream gauge monitoring the Ara watershed (12 km²)

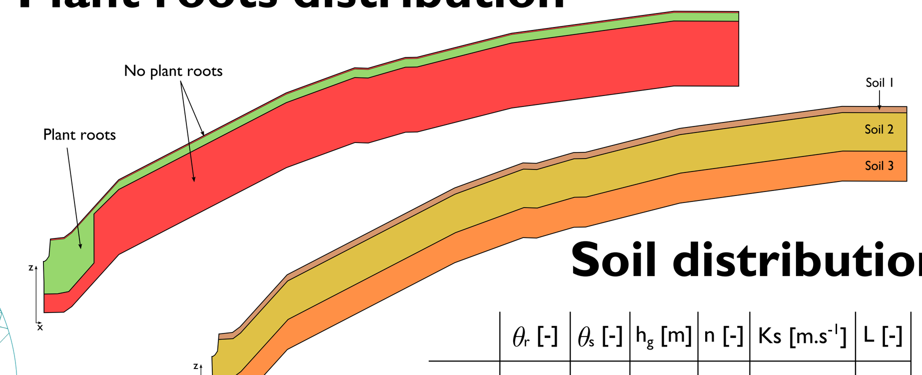
HILLSLOPE: DIFFERENT REPRESENTATIONS

Hillslope schematic approach



Finite element mesh (downslope)

Plant roots distribution



Soil distribution

Soil properties

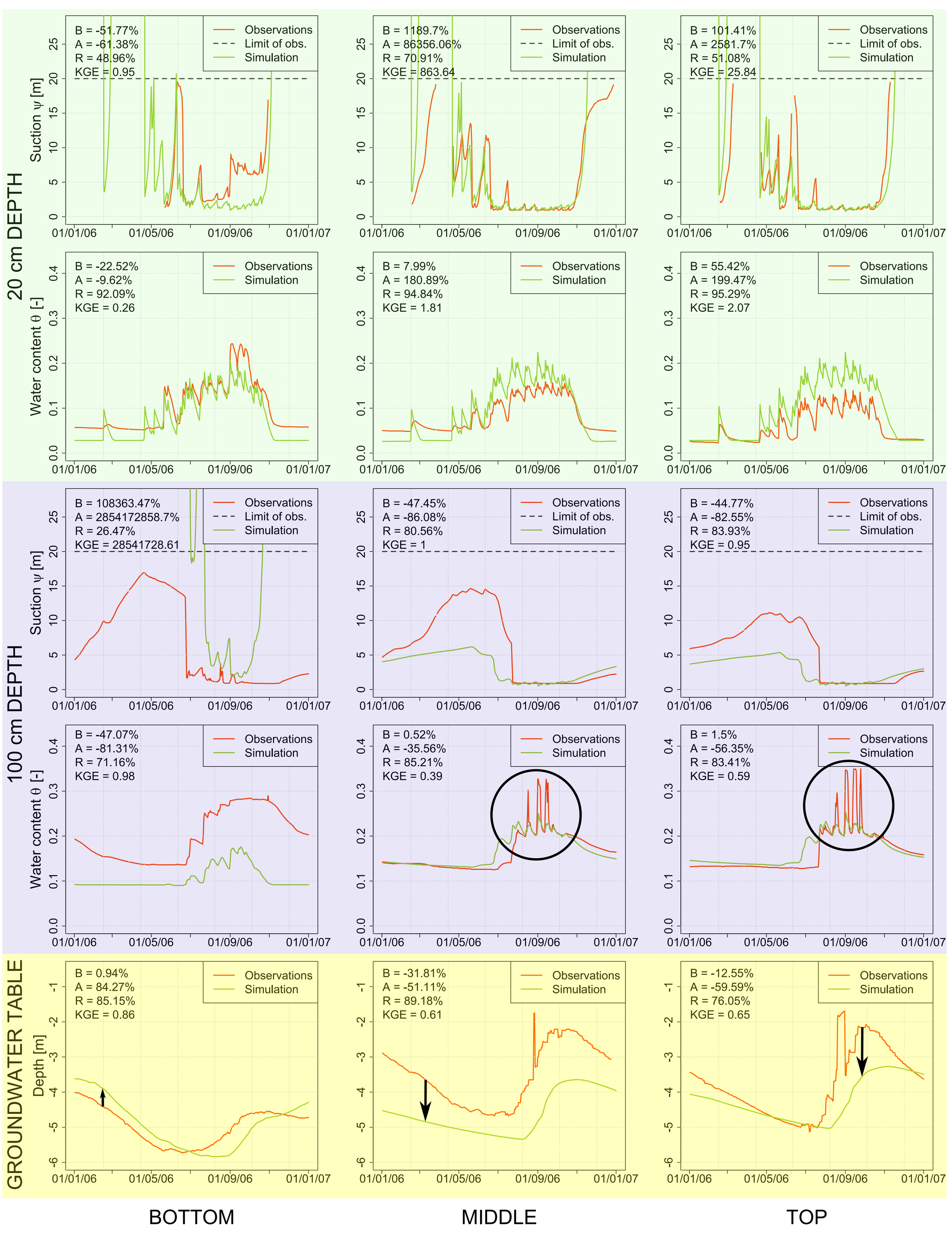
	θ_r [-]	θ_s [-]	h_g [m]	n [-]	Ks [m.s⁻¹]	L [-]
Soil 1	0.025	0.35	-0.50	1.8	$2.3*10^{-5}$	0.5
Soil 2	0.090	0.35	-0.28	1.6	$1.7*10^{-5}$	0.5
Soil 3	0.025	0.30	-1.00	1.8	$3.5*10^{-5}$	0.5

θ_r: residual water content
θ_s: saturated water content
h_g: inflection point pressure
n: pore size distribution index
Ks: hydraulic conductivity
L: pore-connectivity parameter

- 3 soil layers
- Soil layer depth (m): 0 - 0.5 - 3.5 - 6

Photography of the hillslope

RESULTS AND DISCUSSION



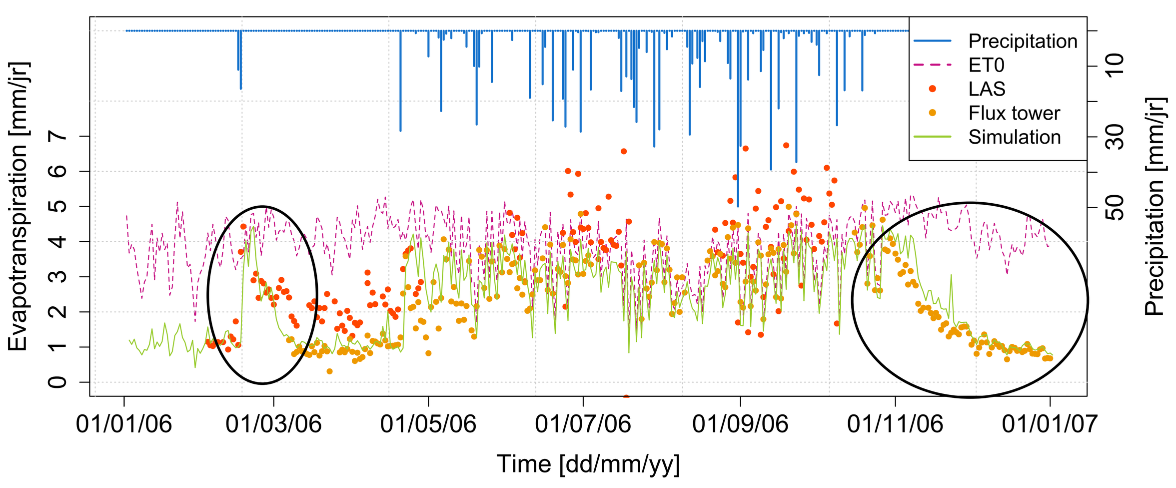
Good fit in the vadoze zone

The annual hydrodynamics at 20 cm and 100 cm depth are in good agreement, but suctions during the dry season are underestimated. At 1m depth, high values of water content (near saturation) during the wet season are not fitted by the numerical modelling.

Slight discrepancy for annual water table fluctuation

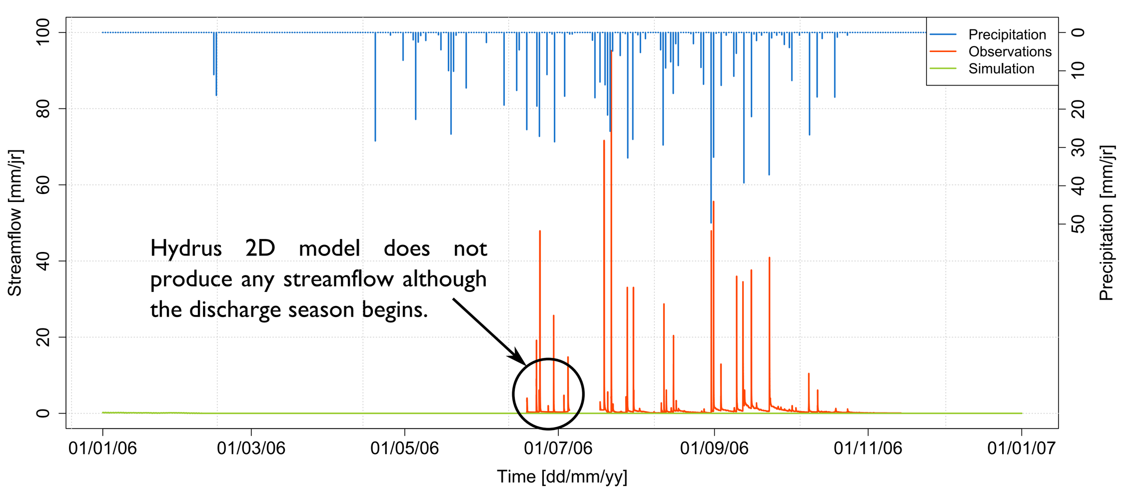
The annual oscillation is simulated with a 20 days delay period. At the bottom of the hillslope, the groundwater table is too high. At the middle and the top of the hillslope, the groundwater level is lower than the observed one with smaller amplitude (arrows on the graphic).

Correct correlation between simulated AET and observed LAS and Flux tower data



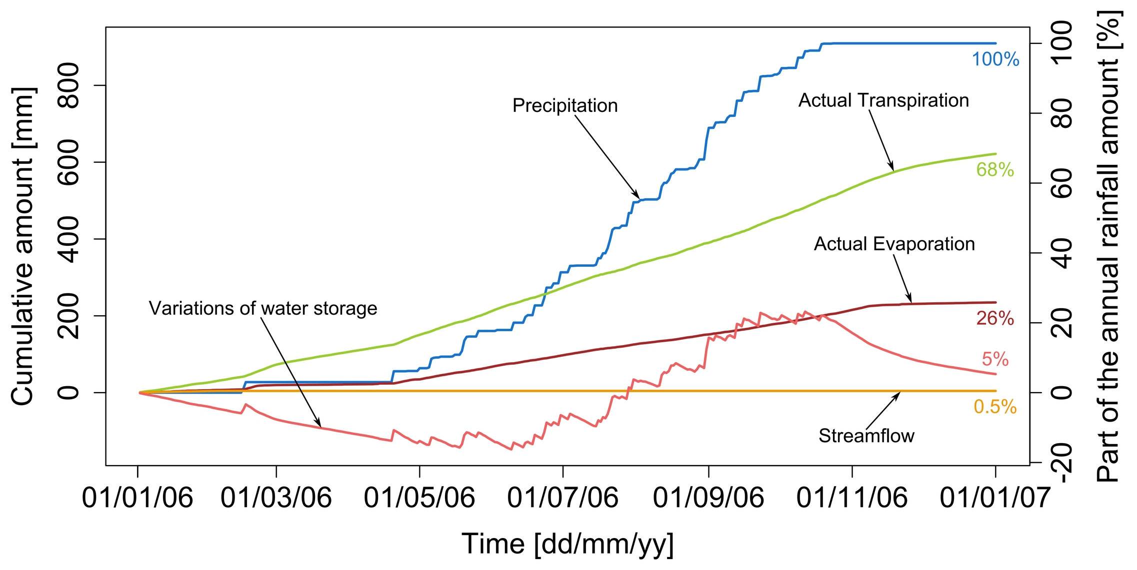
During the wet season the simulated AET reaches the reference evapotranspiration. During the critical periods (the beginning and the end of the wet season), this evapotranspiration is well reproduced (surrounded areas on the graphic). The first evapotranspiration peak of the year is consistent with observations. The November to January decrease is well reproduced.

Poor agreement for streamflow



Streamflows are observed during the wet season in short and intensive events. The model does not simulate any streamflow during the wet season. Moreover the synthetic hillslope produces weak streamflow only during the dry season with a slow dynamics (not visible on the graphic).

Consistent synthetic annual water budget with known AET (2006)



Annual evapotranspiration is the main outgoing flux, which is consistent with Guyot et al. [2009]. Simulated annual streamflow is 0.5 % of the annual rainfall while the observed one represents 13 %. By closure of the water budget, the simulated hillslope storage is positive, equal to 5 % of the annual rainfall.

CONCLUSION

Both 1D and 2D processes are evidenced

The annual hydrodynamics of the vadoze zone and the annual evapotranspiration dynamics are correctly reproduced. Our 2D model catches 1D vertical hydric processes. The hydrodynamic modelling of the hillslope enables us to simulate the annual oscillation of the groundwater table. This study highlights the major role of the 2D water distribution at the hillslope scale to reproduce the groundwater dynamics.

Streamflow generation: detection of "wrong" hydrological processes

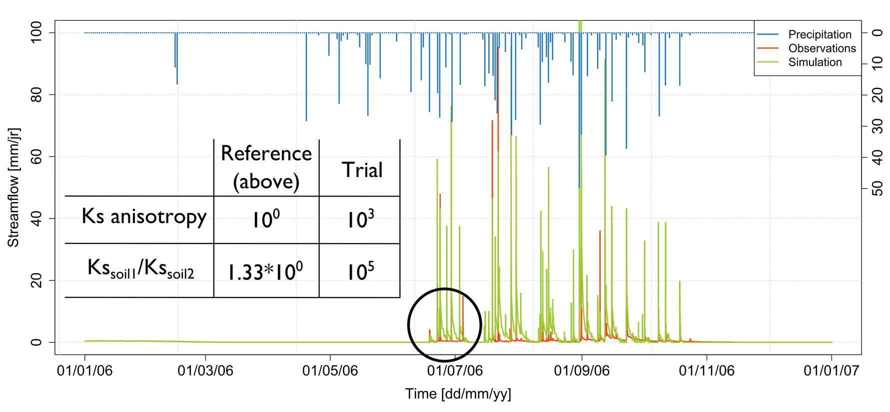
Streamflow is not correctly simulated. Modelled streamflow is produced by a groundwater table rise which reaches up the river. Kamagaté et al. [2007] demonstrated the weak groundwater contribution to river discharge with hydrodynamic, geochemical, and subsurface geophysical investigations. Moreover, Le Lay et al. [2008] well reproduced the hydrologic cycle of the Donga catchment (586 km²) by disconnecting deep water table and river network and producing discharge only with subsurface flows. Our model does not simulate saturated layers which produce subsurface flows. Therefore, our simulated streamflow seems to be produced by "wrong" hydrological processes.

PERSPECTIVES

To enhance the modelling, the question rises: which additional complexity is needed to simulate correctly the streamflow ?

- Higher gradients of Ks between horizons ; Ks anisotropy (illustrated below)
- Dual permeability of Ks to simulate subsurface flows and vertical transfer
- "Bas fond" processes
- Evaluation of the 3D structure of the regolith with Hydrus 3D

Only extreme values (see table) enable us to simulate the first streamflow the same day than the observed one (surrounded area on the graphic). The synthetic streamflow dynamics is correct but the volume outflow is too important (330 % of the observed one).



	Reference (above)	Trial
Ks anisotropy	10^0	10^3
Ks_{soil1}/Ks_{soil2}	$1.33*10^0$	10^5

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