Flood severity along the Usumacinta River, Mexico: identifying the anthropogenic signature of tropical forest conversion

Alexander J Horton[1], Anja Nygren[2], Miguel A Diaz-Perera[3], Matti Kummu[1]

(1) Water & Development Research Group, Aalto University, Espoo, Finland

(2) Development Studies, University of Helsinki, Helsinki, Finland

(3) El Colegio de la Frontera Sur-Unidad Villahermosa, Villahermosa, Tabasco, Mexico

WATVUL project: Water and Vulnerability in Fragile Societies

Across the world, there are multiple drivers, both anthropogenic and climatic, that are changing the hydrological functioning of landscapes.
In some areas this has increased growing populations' exposure to water related vulnerabilities.

This project seeks to examine the impact of these drivers, both bio-physical and sociopolitical, focusing on fragile societies.

Flooding is one of the more obvious water related vulnerabilities, with the main drivers being:

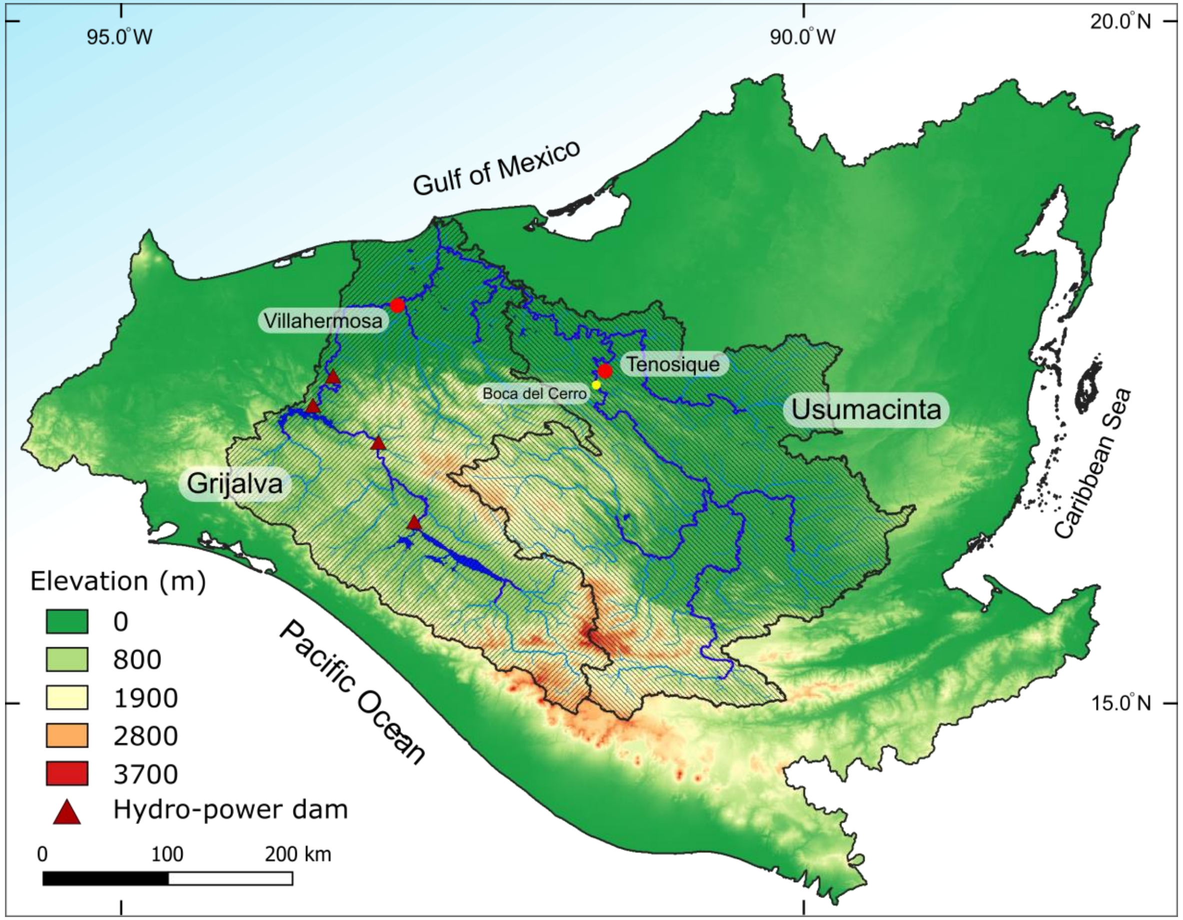
- Land-cover and land-use change through deforestation and agricultural expansion
- Urban expansion
- Water abstraction for consumption or irrigation
- Channel modifications and infrastructural developments (hydropower dams)
- Climate change: shifting precipitation patterns


Avenida Méndez, Villahermosa, Tabasco: 2007 flood

Each of these drivers contributes its own signal to a river's hydrograph.
Yet evaluating the impact of any one in isolation is a challenge due to their interconnectedness, varying climatic conditions.

The signal from forest conversion is particularly difficult to identify and quantify.
large-scale land-cover change historically takes place over long periods, amid many competing developments, and often during times with poor climate and discharge records.

Usumacinta River: Boca del Cerro catchment



Opportune location to study the impact of tropical forest conversion in isolation.

River-basin development concentrated along the Grijalva River sub-basin.

Agricultural expansion didn't intensify until 1990's in the Usumacinta sub-basin.

Discharge and Climate data from Boca del Cerro catchment from 1950's.

Discharge record captures the response of this large river to large-scale rapid forest conversion.

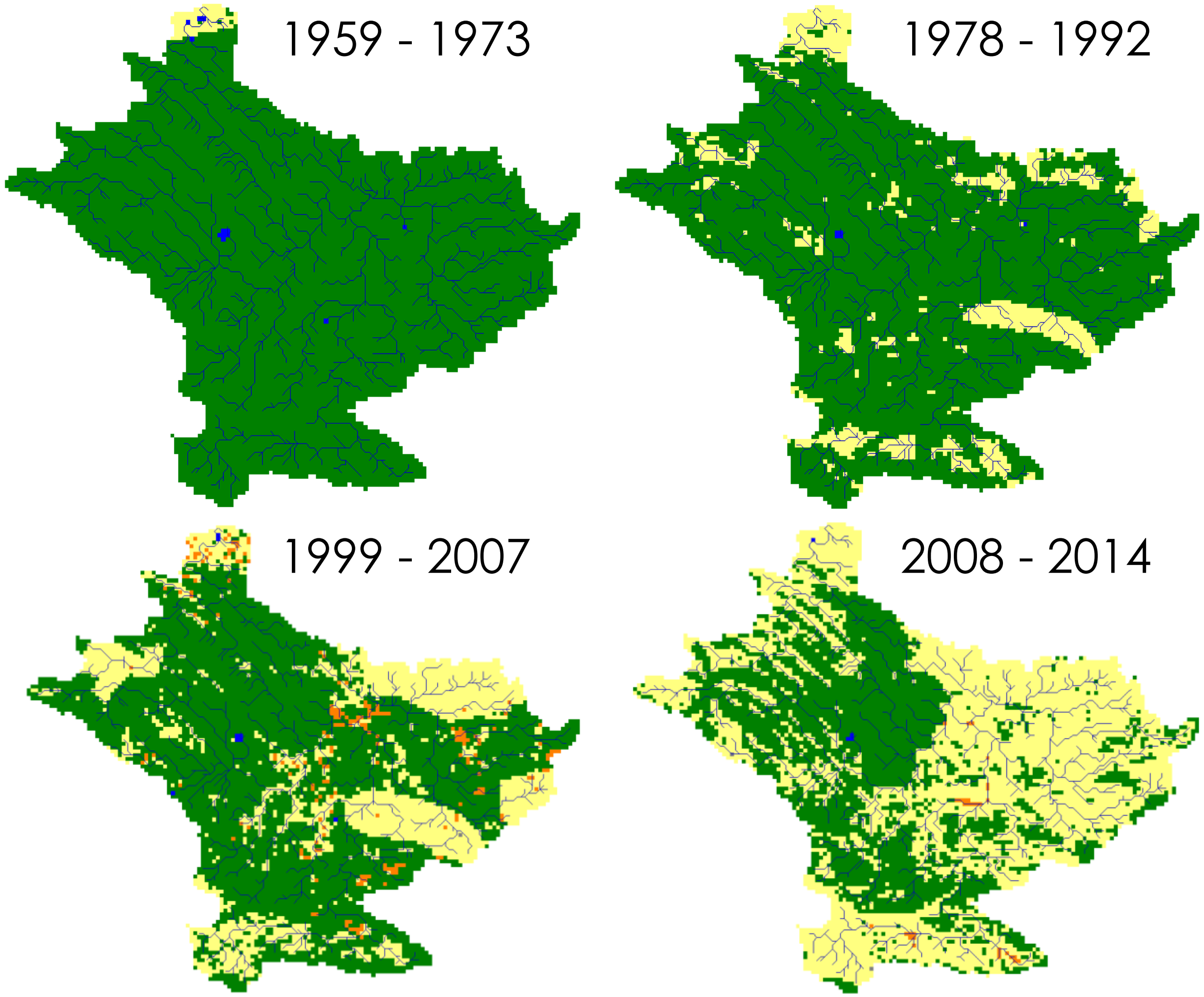
Usumacinta-Grijalva rivers:

- Largest in Mexico – combined account for 30% of surface runoff
- Combined catchment area: 130,000 km^2
- Boca del Cerro catchment area: 53,000 km^2
- Mean annual discharge ~2000 m^3/s at marked gauging station

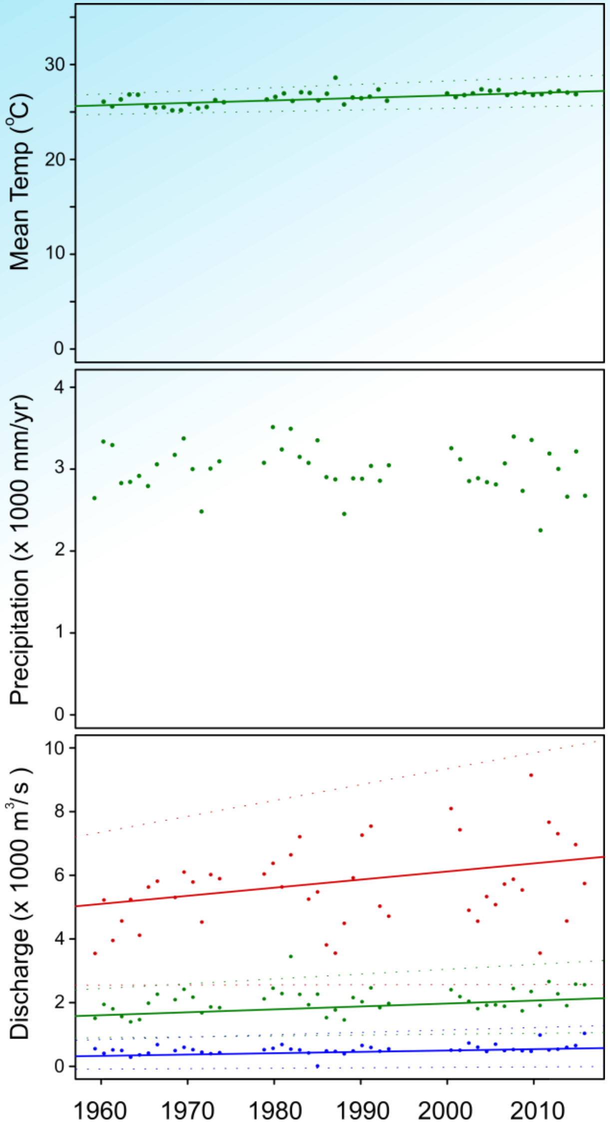
Distinct land-cover periods

We split discharge and climate data into 4 periods representing distinct stages of deforestation.

The periods reflect times of agricultural intensification and times of consistent data.



Observation data analysis: long term trends



Statistically significant positive trend in mean annual temperature (p-value < 0.01)

No statistically significant trend in total annual precipitation, or seasonal precipitation.

Statistically significant positive trend in annual low flow (Q95), mean, and maximum discharge (p-value < 0.01).

Observation data analysis: land-cover comparisons

Temperature: little variation.

Precipitation: significant variation both intra-annually and between time periods.

Discharge: significant variation both intra-annually and between time periods.

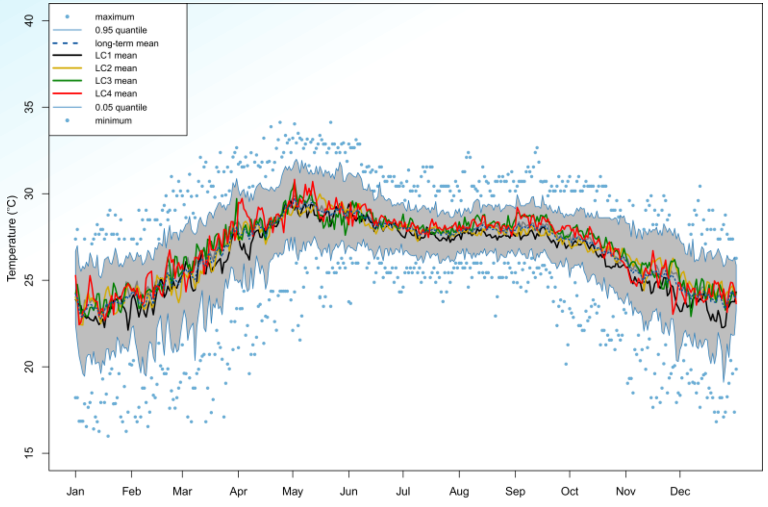
Any signal of deforestation in the discharge record is intertwined with the signal from precipitation

We normalised the daily discharge record by average catchment-wide precipitation totals for the previous 90-days (Figure 4).

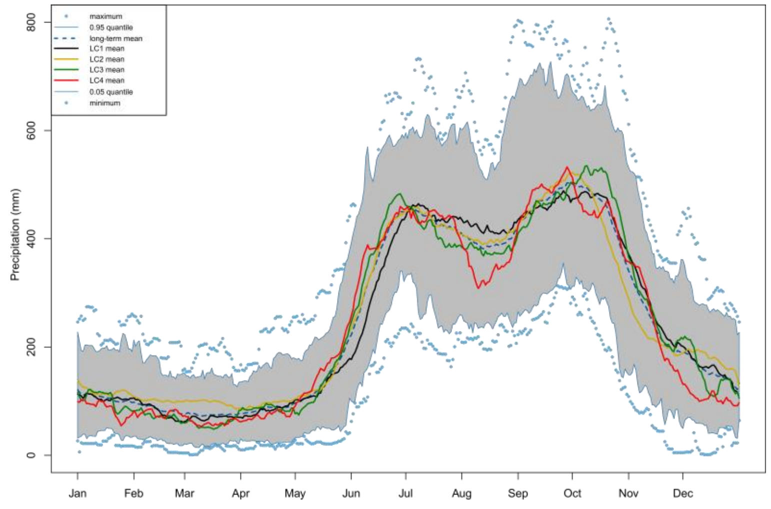
In a static landscape, this proportionality should remain consistent across time-periods as rainfall losses in this catchment are a reflection of evapotranspiration (no extraction or dams) and flow pathways.

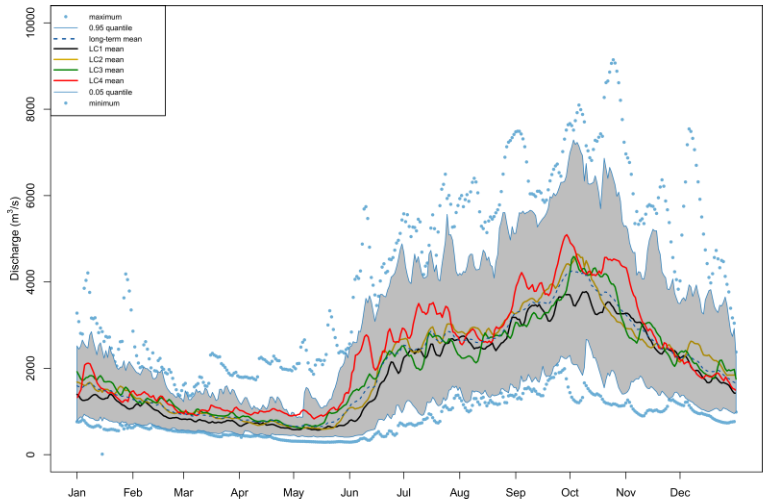
Therefore, the variation displayed in the proportion of rainfall entering the river network is the anthropogenic signal of forest conversion.

Temperature

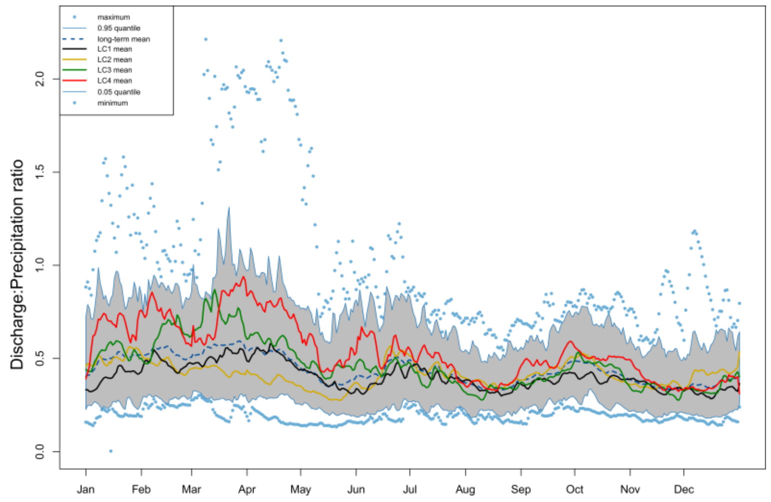


Precipitation



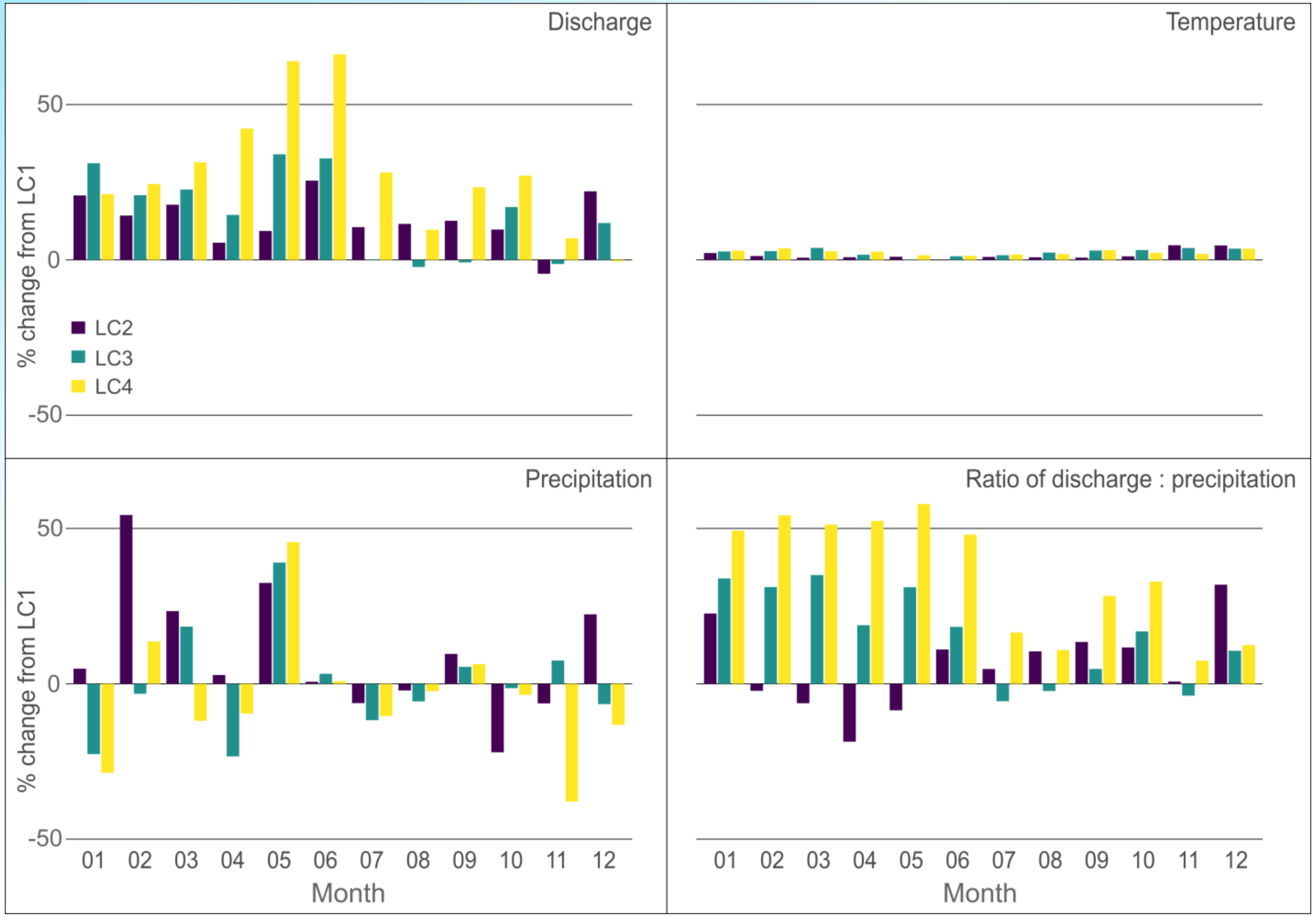


Discharge



Ratio of catchment-wide precipitation to discharge

Observation data analysis: % change from base case (1959-1973)



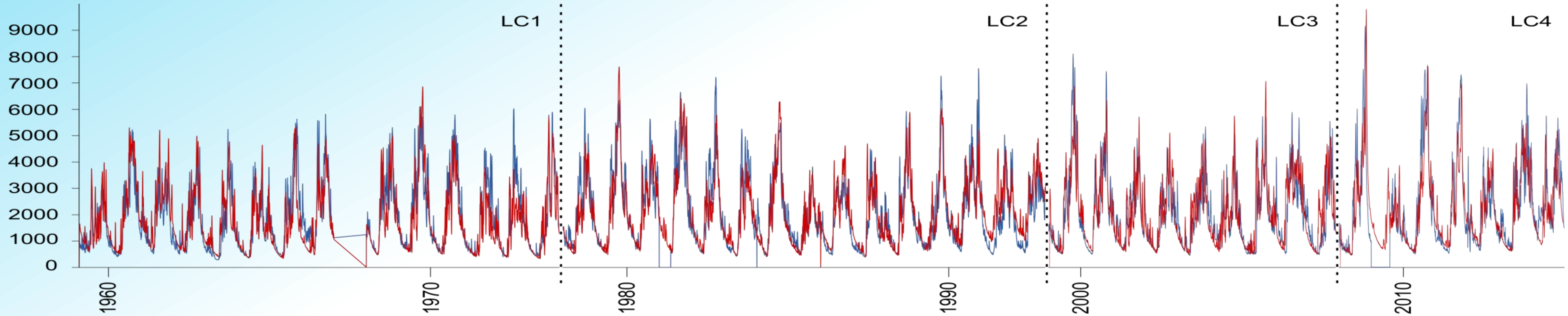
Discharge: significant increase to mean monthly values in later stages of deforestation – particularly at the start of the wetter season (May-June).

Ratios: Clearly significant increases in the proportion of rainfall entering the river network, especially in the drier months (Jan-June).

Findings consistent with notion that forest conversion reduces interception losses and evapotranspiration. These are most noticeable in drier periods with less intense rainfall events.

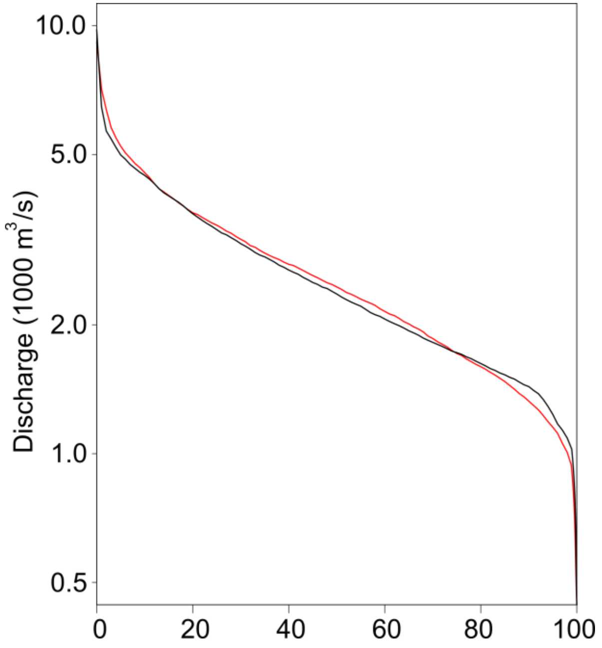
Previous studies less clear about the effect on storm-flow generation and flood magnitude…

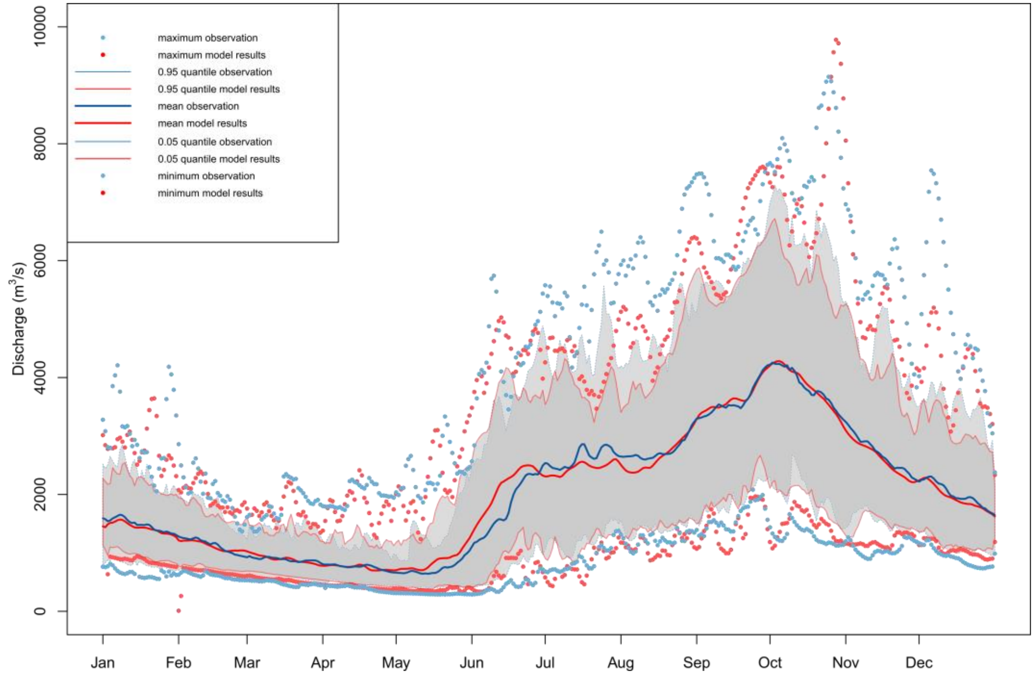
Model application: reproducing the signal



We fitted a model.

And it was good.



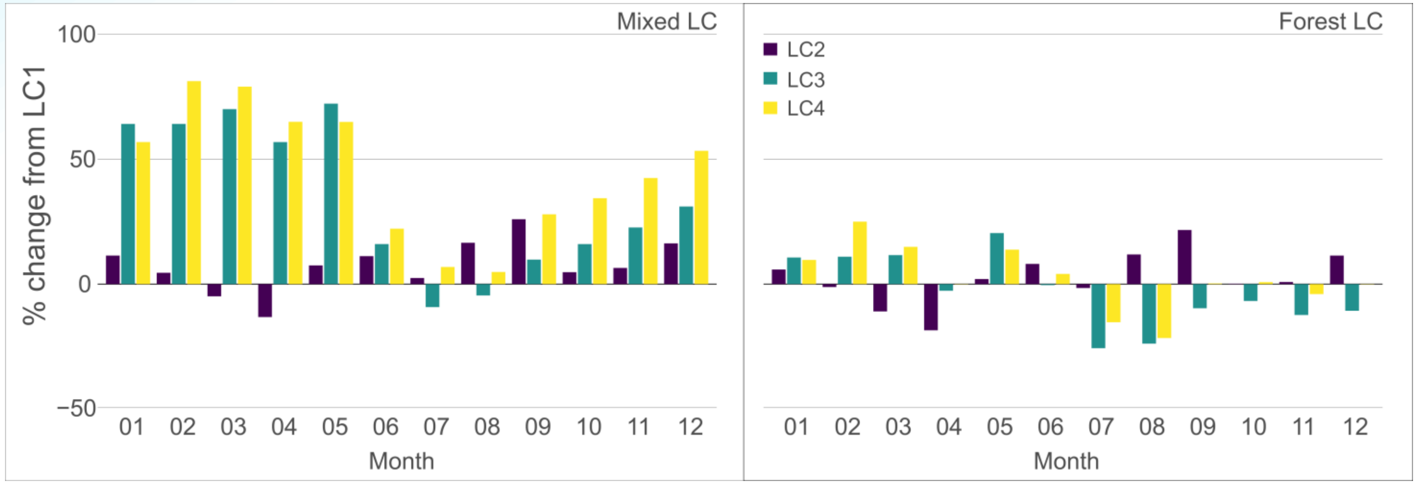


Maintaining a consistent parameterization for the entire discharge record changing only land-cover classifications between periods. For discharge 1959-2014: NSE 0.76; r^2 0.87.

Model application: reproducing the signal

Having fit the model (VMOD), we were able to replicate the same increase in the proportion of rainfall entering the river network in the latter time-periods

We then re-ran the model with the same climate data but simulating total forest cover for all time-periods



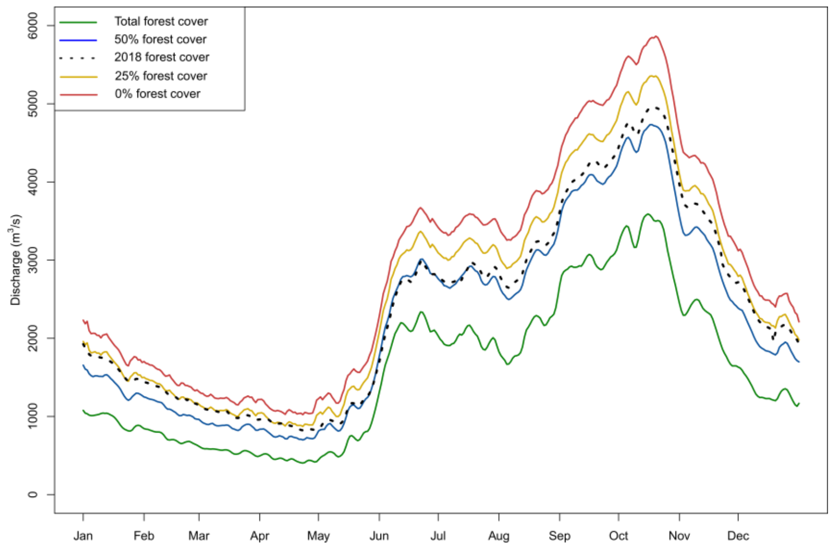
In the absence of agricultural expansion, we find a consistent proportionality in the amount of rainfall reaching the river network.

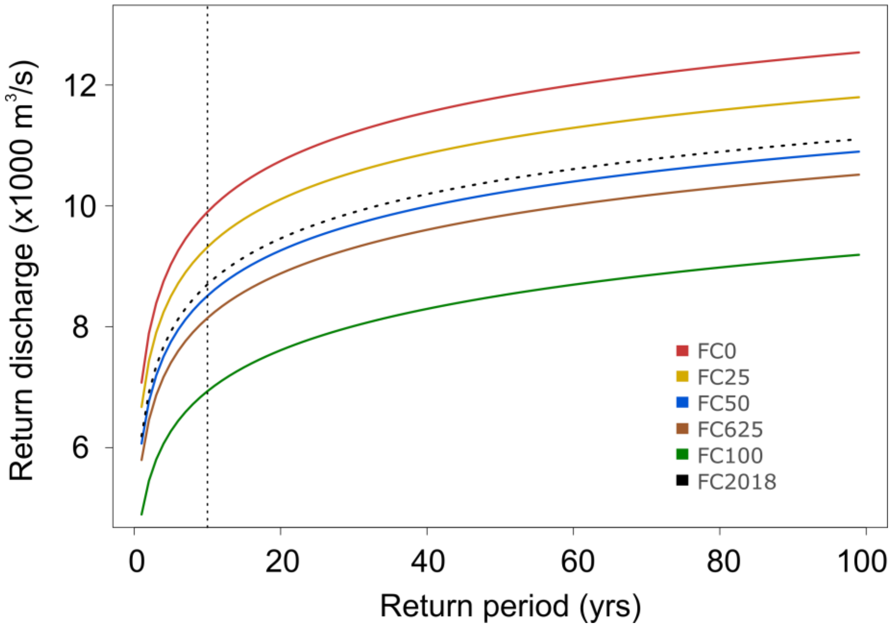
Flood impact analysis: historic and future

To quantify the impact forest conversion has had on the flow regime and flood frequency-magnitude distribution of the Usumacinta River historically, and to estimate the impact it may have in the future, we ran the most robust period of climate forcing data (1999-2018) with scenarios of forest cover ranging from 100% - 0%.

Our results suggest forest conversion alone is solely responsible for raising the magnitude of the 10-year return flood event by 25% over the past 40 years.

Further agricultural expansion at the expense of tropical forest could raise the expected 10-year flood an additional 18%.





Implications

At present, the flood prevention measures within the Grijalva-Usumacinta river basin concentrate on infrastructural developments designed to redirect flood waters away from urban centres.
In light of the economic valuation a 25% increase in flood magnitude represents, we suggest the main water authority of Mexico (CONAGUA) move towards a more integrated approach that includes comprehensive river-basin land-use and resource management practices.

At the global scale, our results quantify the impact tropical forests have on controlling and potentially mitigating large-scale flooding, and demonstrate the utility of incorporating forest conservation and management strategies into flood prevention at the river-basin scale.