Quantifying the non-linearity of the response of Malagasy watersheds to precipitation anomalies

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Résumé

Nous présentons les résultats d'une analyse de données satellites sur l'évolution de l'humidité du couvert végétal et des précipitations pour les différents bassins versants de Madagascar allant de 2003 à 2012. L'analyse révèle des différences systématiques entre les bassins versants, notamment un délai entre le maximum de l'humidité du couvert végétal et le maximum de la pluie qui est systématiquement plus bref pour les bassins versants sans sources en haute altitude que pour les bassins versants ayant des sources à plus de 2000m d'altitude.

Mots-clés : Végétation; bilan hydrologique; Madagascar; bassins versants.

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1 Introduction

The central premise of the theory proposed by Wilmé *et al.* in 2006 (which will be referred to here as WGG06), to formulate an objective definition of the centers of micro-endemism in Madagascar, is that Malagasy river catchments with headwaters at relatively low elevations were zones of isolation and hence led to the speciation of locally endemic taxa, while those at higher elevations were able to maintain their hydrological balance when the climate was cold and dry, and hence contain lower levels of micro-endemism (Wilmé *et al.* 2006, Mercier and Wilmé 2013). The explanation for this difference can be understood as the different local response to periodic droughts. The main hypothesis is that orographic precipitation would have allowed the river systems whose headwaters lie in upper montane zones to maintain more mesic local conditions, in contrast to watersheds with sources at lower elevations and hence with inferior or non-existent orographic potential, which would therefore have experienced greater stress during droughts. The implication is that we can then consider two types of refugia according to the elevation of their headwaters: (1) riparian refugia

along the main courses of rivers with headwaters at high altitudes and where the conditions remained stable during the dry periods; and (2) refugia within the centers of endemism, typically in groups of watersheds with headwaters at lower altitude, where entire populations of plants and animals could have been isolated for a long period when the climate was dry.

Rigorously validating such a theory is quite difficult, because it proposes a sufficient mechanism, not a necessary one. The theory merely proposes a scenario to explain narrow-ranged endemic species with abiotic factors including the non-linear response of the watershed to drought, in the absence of orographic forcing. This intriguing notion naturally begs the determination of the extent to which the different watersheds around Madagascar do respond differently to precipitation and to the inter-annual precipitation anomaly. This was the goal of the analysis that is summarized here: to determine the extent to which the different watersheds respond differently to precipitation and to precipitation anomaly.

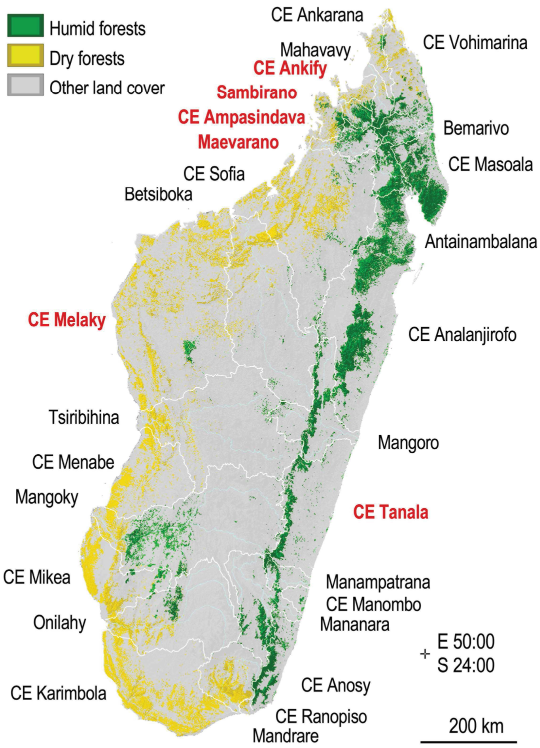
2 Methods

The first step in the analysis was to collect time series of systematic basin-specific observations that can quantify the response of individual watershed to rainfall and rainfall deficits. What observations are available systematically at sub-watershed resolution over a significant time interval? Point observations, e.g. from surface weather stations, do not begin to provide any meaningful characterization of the response of an entire watershed. Observations from space have shed some light on the problem, so far mainly in the form of the « Normalized Difference Vegetation Index » (NDVI), which can be derived from different orbiting optical sensors. Indeed, Ingram and Dawson (2012) report on their comparison of NDVI (albeit derived from the NOAA AVHRR sensors) with the ENSO index produced by the Japan Meteorological Agency from 1982 to 2000. Comparison of the two time series does not appear to be definitively conclusive, and Ingram and Dawson single out the negative correlation between the values of the two indices for the month of October, -0.66 over the 17 years (1982 to 1998, inclusive), with NDVI representing the average value of the index over the entire island. This would indicate that the El-Niño (resp. La-Niña) phase of ENSO is consistent with lower (resp. higher) October NDVI values over Madagascar, indicating a tendency towards less (resp. more) greenness than the mean for that month over the 17 years. As Ingram and Dawson themselves point out, this tendency is contrary to the tendency reported by Jury (2003). Indeed, great care should be taken in making further inferences from this observation, mainly because the NDVI values represent the normalized difference of the spectral reflectances at two bands (near-infrared minus visible) of the pixel being observed on the surface – while this index has been used variously to make estimates of the underlying Leaf Area Index, biomass, chlorophyll concentration in leaves, plant

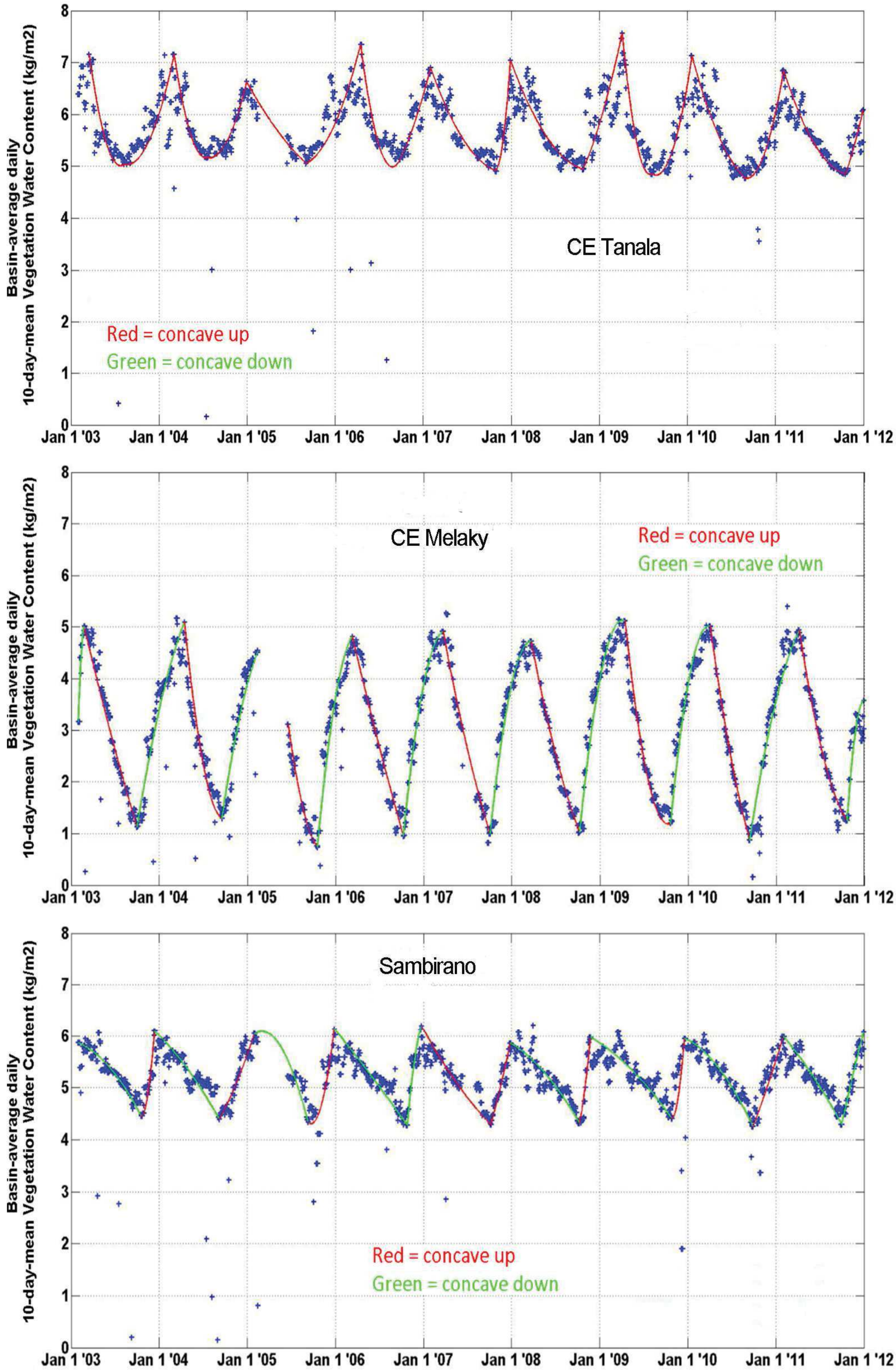
productivity, and fractional vegetation cover in that pixel, it is not a direct measure of any of these quantities. On the other hand, microwave observations are physically directly related to the water content of the pixels being observed, specifically the soil moisture and the vegetation water content (VWC) in the pixel. Sorting out the two contributions and, hence, estimating the vegetation water content requires simultaneous measurements from different channels, either different polarizations at a given frequency band (such as the up-coming Soil Moisture Active Passive satellite will soon be producing, at a low frequency that will be most sensitive to soil moisture and, if the biomass in a pixel is significant enough, to the vegetation water content to a lesser extent) or different frequency bands as in the case of multi-frequency microwave radiometers such as WindSat or the microwave imager on board the Tropical Rainfall Measuring Mission (TRMM) satellite. Because of its higher-frequency channels, the latter turns out to be quite sensitive to VWC, and we have therefore used the estimates of VWC obtained from WindSat by Li et al (2010). The estimates are obtained by a Bayesian approach, using the 10 coincident brightness temperatures measured by the WindSat radiometer (in 5 microwave frequency bands from X to Ka bands, at H anf V polarizations), with a parametric relation between the brightness temperatures on the one hand and the soil moisture and VWC on the other. We have considered the data collected on three distinct hydrological entities as defined by Chaperon *et al.* (1993), along the Eastern slopes, Western slopes and Tsaratanana slopes, namely according to the toponymy proposed by Wilmé *et al.* (2012), the Tanala center of endemism with several watersheds covered with humid forests, the Melaky center of endemism, and the three adjacent monsoon-mediated basins in the the Sambirano region (with high headwaters in the Tsaratanàna) (Figure 1).

3 Results and discussion

The data collected on the two centers of endemism and the group of the three watersheds are illustrated in Figure 2 (see also Stampoulis *et al.* 2014).



The reason these three basins were selected for this report to illustrate the results is that they represent the three regimes of inter-annual behavior that were consistently observed in the data: a) the slow-uptake/rapid-release of water



Basin-average daily
10-day-mean Vegetation Water Content (kg/m2)
CE Tanala
Red = concave up
Green = concave down
CE Melaky
Red = concave up
Green = concave down
Sambirano
Red = concave up
Green = concave down
Jan 1 '03
Jan 1 '04
Jan 1 '05
Jan 1 '06
Jan 1 '07
Jan 1 '08
Jan 1 '09
Jan 1 '10
Jan 1 '11
Jan 1 '12

evident in the CE Tanala (VWC consistently concave up as a function of time); b) the slow-uptake/slow-release of water evident in the Sambirano region (the concave-up/concave-down intra-annual pattern is broken only the November'06-October'07 year); c) the rapid-uptake/rapid-release of water evident in the CE Melaky (consistently concave-down/concave-up water content as a function of time). While this observation is remarkable in its consistency, it is the correlation with departures by the precipitation from its mean that are most interesting for this analysis. Unfortunately, obtaining time series that capture the precipitation anomaly in each watershed proved far more difficult than anticipated. Surface rain-gauge data for Madagascar are patchy, both temporally and spatially, and surface-precipitation products derived from satellite observations suffer from the large uncertainty of remote-sensing retrievals of rain over land, including the correct identification (detection) of precipitation as opposed to non-precipitation cloud especially in pixels where orography plays a role not just in the triggering of condensation but also in the enhancement of precipitation. Among the precipitation products that allow comparisons on temporal scales of the order of 10 days or finer and on spatial scales that represent and resolve individual watershed, the one that appeared to be most consistent with monthly rain gauge data ("monthly" because gauge data are not reported with sufficient density or with consistent observational intervals to allow meaningful comparisons on shorter time scales) is the TRMM Multiple satellite Precipitation Analysis (TMPA), also known as TRMM 3B42 (Huffman et al, 2007). This product is the result of a calibration-based sequential scheme for combining precipitation estimates from multiple satellites, as well as gauge analyses where feasible, at fine scales (0.25° x 0.25° and 3 hourly).

Figure 3 allows a comparison between the precipitation product used in this analysis and the rain-gauge-derived surface rainfall, accumulated over a two-year period.

Figure 4 shows the precipitation anomaly according to TMPA for the three groups of watersheds selected from figure 1. The time series are quite representative of the general joint behavior of the Southern Oscillation Index and the rain anomaly over the different watersheds, and points to a general trend toward rain deficits during La Niña and excess rain during El Niño, confirming the trend reported by Jury (2003). However, the basin-specific and season-specific details do turn up instances of the opposite behavior, of which Ingram and Dawson provide some anecdotal evidence. More sweeping or even systematic inferences would be difficult to justify given the substantial uncertainties in the precipitation estimates.

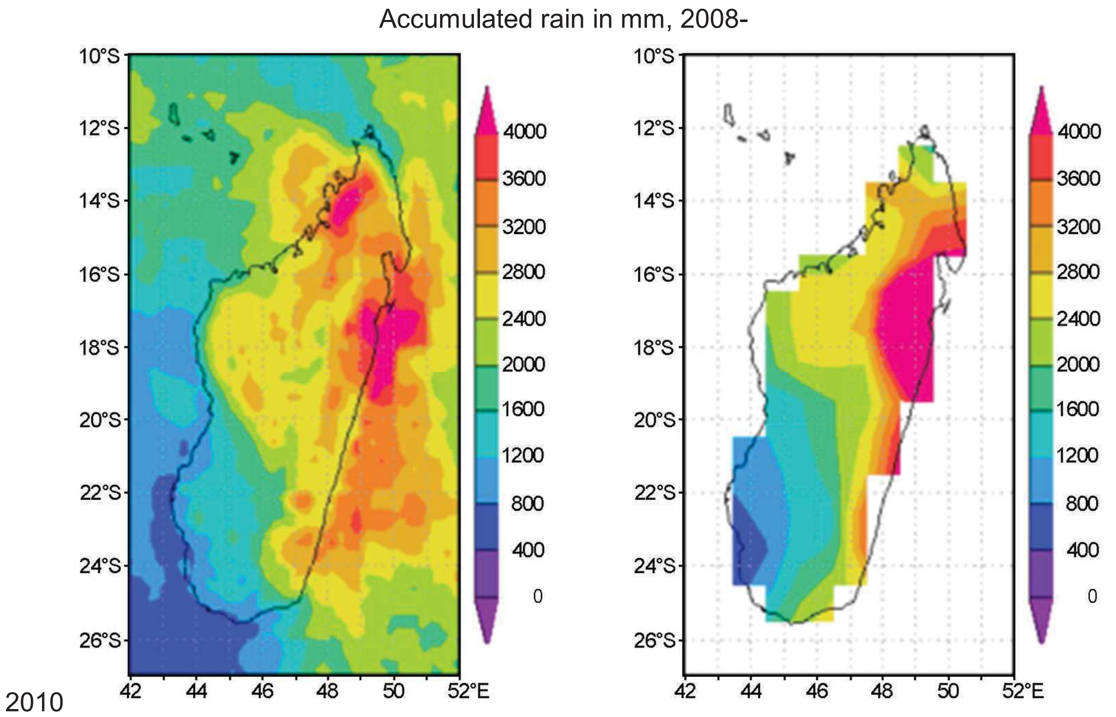


Figure 3. TRMM Multiple satellite Precipitation Analysis (3b42 version 6) surface rain accumulation (in mm) from October 2008 to October 2010 (left), with the GPCC rain gauge accumulations over the same period for comparison (right).

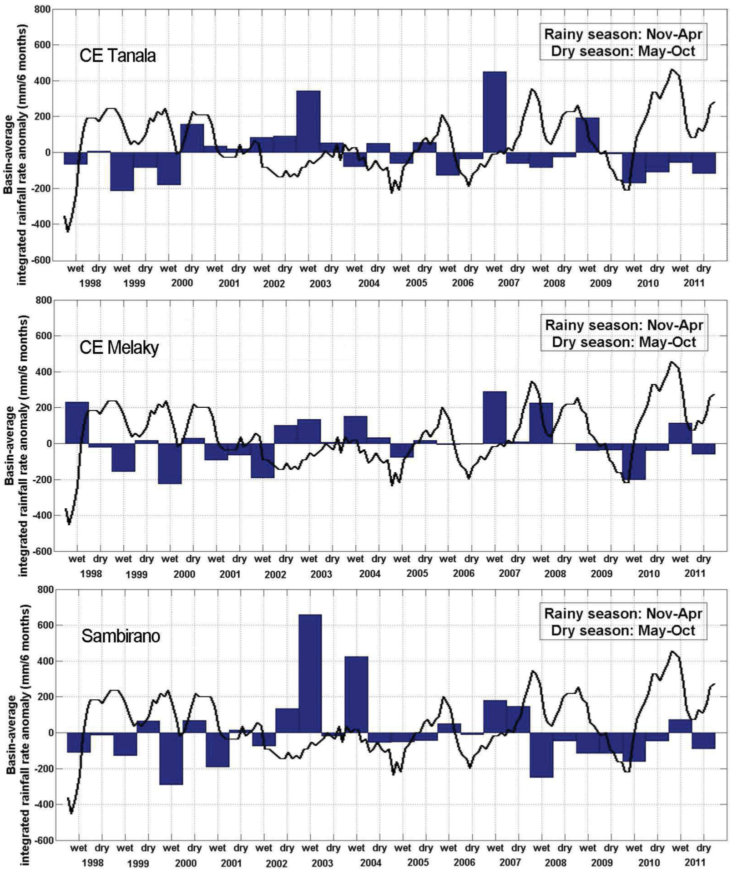


Figure 4: semi-annual rain anomaly for the three watersheds of figure 1, with the Southern Oscillation Index curve in black (negative values corresponding to El-Niño periods).

Finally, the joint analysis of the basin-specific vegetation water content (and soil moisture) time series, on one hand, and the precipitation and precipitation anomaly time series, on the other, led to the following conclusions:

- High-headwaters basins have a systematically longer delay (of about 52 days) from the annual precipitation peak to the vegetation water content peak than low-headwaters basins (where the delay is around 41 days).

- The wet-season-integrated surface rain is correlated with (wet+dry)-season-integrated VWC (figure 5), whether one considers high-headwaters basins or low-headwaters basins. However the joint variability in the former is roughly linear and suggests a more synchronized response to the precipitation, whereas the 12-month-integrated VWC in low-headwaters basins appears to saturate around 1500 kg/m2. To make these conclusions, we had to eliminate the CE Anosy (see figure 1) which was tenuously represented by only two pixels in our analysis. Note that the only other watershed that was equally tenuously represented, the Bemarivo basin, is also responsible for the outliers in the numbered-basins panel in figure 5. The Manombo, Ampasindava and Ankify centers of endemism could not be represented as their microwave data are too uniformly close to the coast to be unambiguously interpreted.

- There did not appear to be any significant correlation between integrated VWC and rain anomaly in either the low-headwaters class of basins or the high-headwaters class.

- There does not seem to be any significant correlation between VWC delay and precipitation amount, or between VWC delay and the precipitation anomaly.

- The total rain accumulation in the high-headwaters basins is not significantly different from the total accumulation in the low-headwaters basins. This suggests that the precipitation estimates that we started with do not adequately capture the orographic enhancements, though they are consistent with the location of the Malagasy topographic « backbone » and, therefore, do capture the zeroth-order topography.

This study is a first step in the quantification of the hydrologic properties derived from microwave remote sensing, and is now being improved by incorporating Ku-band scatterometry observations over the different basins.

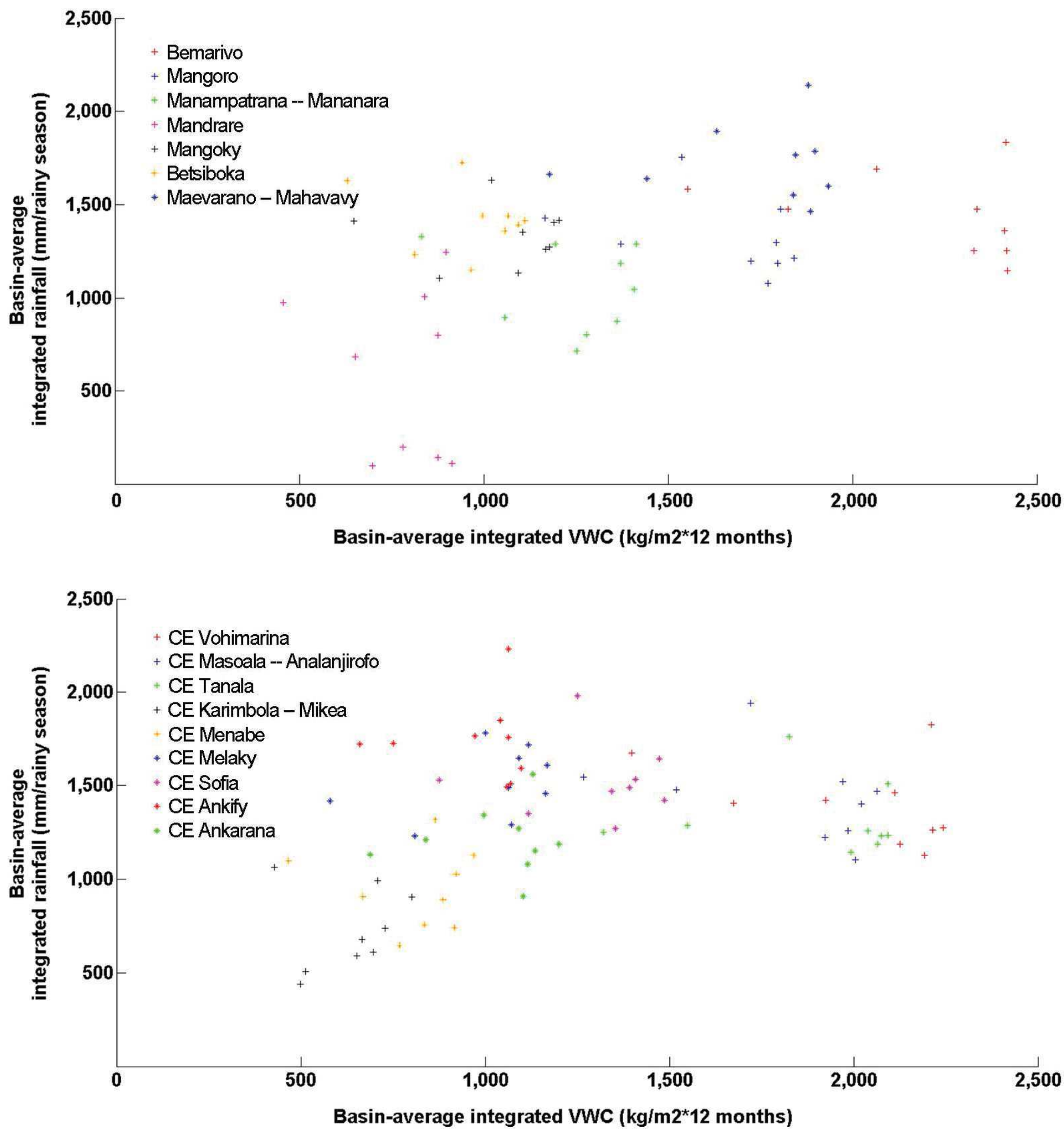


Figure 5: Correlations between integrated rain and integrated VWC for high-headwaters (top) and low-headwaters (bottom) basins.

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