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Experiences in using the TRMM data to complement rain gauge data in the Ecuadorian coastal foothills

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Abstract

Nowadays, new technologies are being used to expand the coverage of conventional meteorological datasets. An example of these is the TRMM data as long as one considers the bias, the type of rainfall and the current coarse spatial resolution. Although in the Guayas River Basin (Ecuadorian lowlands) the radar-based precipitation does not match the magnitude of the ground-based rainfall, at least it records somewhat the spatial pattern. The bias remains more or less steady when the temporal resolution increases from yearly to seasonal and monthly data. By means of an empirical disaggregation method, synthetic daily rainfall time series were generated at the satellite measuring spots. These artificial series were incorporated into an existing hydrological model to complement the available raingauge data to assess the model performance. The results were quite comparable with those using only gauge information. Although the model outcomes did not improve remarkably, the contribution of this approach was based on the fact that given a known bias, the satellite data could still be corrected and may resemble the information provided by the raingauges. Therefore, TRMM may supply valuable information in areas scarcely gauged such as the Andean foothills in the Guayas River Basin.

1 Introduction

Nowadays, remote sensing is immensely useful to improve our understanding of spatio-temporal variation of rainfall, particularly for data scarce regions. In this regard, the Tropical Rainfall Measuring Mission (TRMM) (Simpson et al., 1988; Kummerow et al., 1998), an initiative of the US Space Agency (NASA) and the Japanese Aerospace Exploration Agency (JAXA), is instrumental in shaping the research related to the use of satellite based rainfall products in hydrological studies (http://trmm.gsfc.nasa.gov/). TRMM is operational since November 1997 and is releasing products since 1998.

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As its name indicates, the TRMM mission covers only the tropical zone, i.e. between the latitudes 50° N and 50° S. The current spatial resolution is 0.25°. The satellite possesses five instruments on board: (i) the Precipitation Radar (PR) which records the intensity, distribution, type of the rain, the storm depth and the snowmelt height, with a swath width of 215 km; (ii) the Microwave Imager (TMI) which senses the microwave energy emitted by the planet and the atmosphere, with a width of 760 km; (iii) the Visible and Infrared Scanner (VIRS) which measures the radiation originated in the planet in several spectral zones, with a swath width of 720 km wide; (iv) the Clouds and the Earth's Radiant Energy System (CERES) which measures the energy levels in the highest region of the atmosphere as well as on the Earth's surface; and (v) the Lightning Imaging Sensor (LIS), the intra-cloud and cloud-to-ground lightning detector.

A large number of publications have reported worldwide experiences on the use of TRMM products (Nicholson, 2005; Hughes, 2006; Collischonn et al., 2008; Wong and Chiu, 2008; Buarque et al., 2011; Rollenbeck and Bendix, 2011), particularly the 3B42 type (Huffman et al., 2007). In this regard, two lines of research are noticed. The first one have been focusing on comparing the TRMM rainfall data with the rain gauge data, either to study the spatial and temporal variability, or to test the validity of the TRMM products. The second line of research has investigated the potential use of the TRMM rainfall data as an independent data source or in complementing rain gauge data for hydrological studies.

There are important works related to the first category. For instance, in the arid environments of southern Africa, Nicholson (2005) and Hughes (2006) reported that the TRMM data overestimated the raingauge data in every comparison based on a monthly scale. Other interesting cases are the ones reported by Bell and Kundu (2003). They also compared on a monthly basis and recognized that even in densely gauged networks there were large differences between ground data and TRMM data. A number of studies have reported that the comparison on annual time scale yields very good results but with finer temporal scales the error starts increasing. At daily or weekly time resolution, error values around 50 % have been reported (Wilheit, 1988; Olson et al., 1996; Huffman et al., 2010). Other examples of comparisons have been performed as well in different places such as Hong Kong (Wong and Chiu, 2008), the Brazilian part of the Amazon River Basin (Buarque et al., 2011), Indonesia (Vernimmen et al., 2012) and countries with poor data conditions such as Ghana (Endreny and Imbeah, 2009).

The location of the selected study area seems to strongly influence the comparison performance. Publications whose case studies deal with oceanic environments or flat areas (e.g. Amazon Basin) report very good match between the data from raingauges mounted on buoys and the TRMM data (Adler et al., 2000; Bowman, 2005). In studies on locations with higher altitudes and particularly in the foothills of mountainous regions (e.g the Andes), there were notorious differences between the two sources of data (Tian and Peters-Lidard, 2010). In this regard, under the orographic effect TRMM might show lower values than the gauge rainfall (Dinku et al., 2010). To worsen the scenario, these areas are frequently the most unattended by the national weather agencies in terms of data availability. Given this background, there is an extreme heterogeneity and uncertainty of the spatio/temporal distribution of the convective rainfall (Bendix et al., 2009). For this challenge, TRMM and in general satellite data may contribute for a better comprehension of the spatial and temporal pattern features of precipitation, in particular if space borne and gauge data complement to each other (Rollenbeck and Bendix, 2011). This possibility still needs to be investigated in areas with large spatial variability of rainfall.

A second group of researchers have gone beyond data comparisons. They have used the satellite products as a new input for rainfall-runoff models and then compared the simulation results with that of the original model. Noteworthy examples are the models developed in California (Guetter et al., 1996; Yilmaz et al., 2005) where flow simulation and soil water estimates were undertaken at a meso-scale basin using the GOES (Geostationary Operational Environmental Satellite) data. Although the simulation outcomes, when compared with the conventional hydrological simulation, were not very accurate, the authors were able to demonstrate a procedure of combining manifold data sources. Possible sources of error may have been: (i) the quality level

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of the GOES atmospheric correction algorithms at that time; and (ii) the fact that the precipitation estimations (Yilmaz et al., 2005) were aimed to ungauged basins, hence involving a large uncertainty. In the Tapajós River (Amazon Basin, Brazil) spatial rainfall as well as daily comparisons of different data sources for hydrological simulations have been investigated. Firstly using only raingauge observations; and secondly, integrating these point measurements with TRMM (Collischonn et al., 2008). These comparisons gave support for large-scale rainfall-runoff and further hydrodynamic simulations (Paiva et al., 2011).

The literature suggests the promising possibility of complementing the rainfall data from raingauges with that from TRMM in hydrological studies of data scarce regions such as the Vinces Basin in Guayas River Basin in Ecuador. This paper presents a simple procedure to combine the two aforementioned sources in hydrological simulation of an existing rainfall-runoff model of Vinces Basin.

2 Framework

2.1 The Vinces River catchment

The Guayas River Basin (GRB, 34 000 km^2) is located within the Ecuadorian coastal region (Fig. 1). It is one of the most important areas in Ecuador, in terms of economic production. Three main activities take place within the basin, namely, urban-industrial development, agriculture and aquaculture (Southgate and Whitaker, 1994; Falconi-Benitez, 2000). More than 68 % of the national crop production originates from this watershed (Borbor-Cordova et al., 2006). The Vinces River catchment is located in the central part of the Guayas River Basin. The Vinces River is the third most important waterway in the region, after the Daule and Babahoyo which form the Guayas at Guayaquil City. The drainage area of the upper part of the catchment is around 3420 km^2 until Quevedo city (total area is 5300 km^2). Elevations range from 60 m (at the outlet) up to 4080 m along the Andean foothills, particularly the north-eastern part.

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Annual rainfall varies from around 1000 to more than 3500 mm (Arias-Hidalgo et al., 2012). The mean historical flow at the upper catchment's outlet is 220 $m^3 s^{-1}$. In general, two seasons are distinguished across the Ecuadorian lowlands: the *rainy* period (wet season), going from mid-December to May and the *dry* during the rest of the year, characterize by a common absence of rainfall.

2.2 The hydrological model

A simulation study was carried out to compute the streamflow contribution from the upper to the lower Vinces catchment as part of a broader study involving a wetland-catchment analysis framework (Arias-Hidalgo et al., 2012). The Lulu and San Pablo Rivers, main tributaries of Vinces, have crucial importance since they may mitigate the effects the Baba Dam project may exert on the lower course of the river (Fig. 1). As such, the main target of that study was to calculate the hydrographs at the confluence of Lulu and San Pablo with the Vinces River as well as at the catchment's outlet. To that end, the aforementioned catchment was divided into 6 subbasins (Fig. 1b) and HEC-HMS (Sharffenberg and Fleming, 2010) was used as the software tool to compute the catchment runoff. The importance of these two tributaries has been acknowledged in previous studies (Efficacitas, 2006).

In general, spatial data are very scarce across the Guayas River Basin. This involves a low number of weather stations, a poor density of available meteorological measurements and long gaps throughout the time series, few available calibration points, etc. Because of these, the model made use of simple techniques that require a limited number of variables to setup the model. Hence, the effects of storage, canopy, interception, infiltration, evapotranspiration and soil moisture, variables whose measurements were insufficient or poor, were represented using the constant loss method (Skaags and Khaleel, 1982; USDA, 1986). Surface water, baseflow variables and gage weights were used as estimated inputs for the computation of imperviousness, lag time, contribution of baseflow to total flow, and rainfall spatial distribution per subbasin, respectively (see Tables A1, A2 and A3). The model was setup and calibrated for the years 2005 and

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2006 against discharge observations at *Quevedo en Quevedo* station. The average Nash-Sutcliffe number (NSC) (Nash J.E. and Sutcliffe J.V., 1970) was around 0.75 (a summary of the NSC numbers for some subbasins is shown in Table A4).

3 TRMM-based methodology and results

Among several TRMM data products, 3B42 data were used in this study as it has been recommended by previous researchers (Winsemius, 2009; Dinku et al., 2010; Almazroui, 2011; Vernimmen et al., 2012). At first, the 3B42 data was downloaded from the geodata website of the King's College in London (http://geodata.policysupport.org/rainfall-timeseries). The three-hourly data throughout a time span of 8 yr (1999–2006) was available, which allowed aggregating the values to a daily, monthly and yearly resolution.

Annual rainfall from raingauges and TRMM data, averaged over the available period 1999–2006, were computed at their respective measurement points. Adopting the Inverse Distance Weighting (IDW) for interpolation, an average spatial distribution of annual rainfall is shown in Fig. 2a, b. The ground-based map indicated an increasing pattern principally towards the north. Such a trend was somewhat also captured by the TRMM-based map, although its order of magnitude was 50–65 % smaller than the raingauge representation. However, the upper-right part of the catchment shows the lowest density of ground based measuring stations. This fact corroborates the concerns about possible high uncertainties that may be associated with rainfall estimation across foothill areas (Paiva et al., 2011).

Several time scales were considered for bias correction: annual, seasonal, monthly, etc. The monthly resolution proved to be the finest one with still a high correlation between the two rainfall data sources (to be described shortly). Monthly bias correction has been adopted in previous researches (Bell and Kundu, 2003; Hughes, 2006; Rollenbeck and Bendix, 2011; Vernimmen et al., 2012). Beyond that resolution, in general

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at the rain stations and at daily scale it was common to find poor correlations between the raingauge observations and the raw TRMM data ($R^2 < 0.30$).

Commonly the raingauge emplacements and the TRMM grid cell centres do not coincide. As a consequence, the average monthly TRMM data at the grid cells had to be estimated at the raingauge locations (IDW was used once again). Thus, the average monthly rainfall values for the study period (1999–2006) measured at each rain gauge location were compared against their TRMM interpolated counterparts. The following equation expresses a relationship between the raingauge and the *uncorrected* TRMM monthly values:

$$\mathrm{TP}_{i,m} = K \cdot \mathrm{TRMM}_{i,m} \tag{1}$$

where K is the bias factor at the raingauge location i. $\mathrm{TRMM}_{i,m}$ is the uncorrected monthly rainfall (mm month^{-1}), obtained from the satellite data and estimated at the raingauge location i during the month m; and, $\mathrm{TP}_{i,m}$ is the total rainfall at raingauge i during the month m (mm month^{-1}), from ground observations.

An example of this correlation can be seen for the Puerto ila station (Fig. 3). Table 1 shows the extended results of this annual comparison (based on monthly scale adjustment). In general, it was observed a high correlation at monthly scale ($R^2 = 0.81$ in average). In that regard, Fig. 4 illustrates a graphical comparison between the ground observations, the uncorrected and corrected TRMM data.

In order to assess the validity of the bias correction, the relative bias and the Root Mean Square Error (RMSE) were calculated as follows:

$$\text{relative bias (\%)} = \frac{P_{\mathrm{Groundst}} - P_{\mathrm{TRMM}}}{P_{\mathrm{Groundst}}} \cdot 100 \tag{2}$$

$$\mathrm{RMSE}\ (\mathrm{mm\,yr^{-1}}) = \sqrt{\frac{\sum_{i=1}^{12} (\mathrm{TP}_{i,m} - p_{\mathrm{TRMM}_i})^2}{12}} \tag{3}$$

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where P_{Groundst} is the annual rainfall from ground observations (mm yr^{-1}). P_{TRMM} is the uncorrected and corrected annual rainfall, derived from the satellite data (mm yr^{-1}). p_{TRMM_i} is the monthly rainfall for month m, at raingauge location i, for both uncorrected and corrected TRMM information (mm month^{-1}).

As a further step, the bias adjustment coefficients (K in Eq. 1) were spatially distributed across the Vinces upper catchment resulting in a distributed map of correctors (Fig. 5). As before, the approach was the inverse distance weight, based on the correctors estimated at each raingauge location. As it could have been expected from the differences in annual averages, bias correctors between 2.7 and 3.2 constituted a representative interval for most of the catchment domain, only with the exceptions of those ground stations situated in the uppermost portions of the catchment (close to the water divide). The correspondent bias correction coefficients were estimated for each of the TRMM grid centres and thus the correction took place using the following expression:

$$\mathrm{TRMM}_{\mathrm{corr},j,m} = K' \cdot \mathrm{TRMM}_{j,m} \quad (4)$$

where K' is the monthly bias factor, estimated at the TRMM grid centre j. $\mathrm{TRMM}_{j,m}$ is the uncorrected TRMM monthly rainfall at the grid centre j during month m (mm month^{-1}); and, $\mathrm{TRMM}_{\mathrm{corr},j,m}$ is the corrected TRMM monthly rainfall at the grid centre j during month m (mm month^{-1}).

Compared to the original setup of the rainfall-runoff model, five TRMM-based rainfall stations were thus incorporated to the simulation (circles in Fig. 5), two in the lower area and three in the highlands. Because the rainfall-runoff model was built using a daily time step, the satellite corrected monthly values needed to be disaggregated to a daily resolution for each new information spot. To achieve this, empirical factors (f_i) were derived from the raingauge precipitation time series as follows:

$$f_{i,d} = \frac{P_{i,d,m}}{\mathrm{TP}_{i,m}} \quad (5)$$

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where $f_{i,d}$ is the temporal disaggregation coefficient, at the raingauge i, for the day d of month m. $P_{i,d,m}$ is the total rainfall at raingauge location i in the day d of month m (from ground observations, mm day^{-1}); and, $TP_{i,m}$ is the total rainfall at raingauge location i during the month m, from ground observations (mm month^{-1}) as explained in Eq. (1).

The $f_{i,d}$ ratios were then applied back to the corrected TRMM monthly values to estimate the daily series (day x, month X) at the satellite grid centres. There, the procedure took the factors from the nearest ground location. The final expression is as follows:

$$\mathrm{TRMM}_{\mathrm{corr},j,d} = f_{i,d} \cdot \mathrm{TRMM}_{\mathrm{corr},j,m} \quad (6)$$

where: $\mathrm{TRMM}_{\mathrm{corr},j,d}$ is the disaggregated, daily corrected TRMM monthly rainfall at grid centre j (mm day^{-1}).

The iterative process continued until the simulation time span was completed. Finally, in order to illustrate the validity of this simple procedure, an example was taken from the location of the Puerto ila gauge station, as it is shown in Fig. 6. At daily scale, the correlation at this spot was high enough ($R^2 = 0.88$) given the empirical approach and the large initial bias.

4 Performance of complementary TRMM data for the HMS model

The HEC-HMS model of the Vinces River catchment was run for the year 2006, in principle with the data from raingauges exclusively; and afterwards using the former and the TRMM data together. For the first sort of simulation, Fig. 7 shows an example of hydrograph comparison between observed and computed values, at the *Quevedo at Quevedo* streamflow station. It was observed that although some of the observed peaks were not accurately matched by the simulation, at least the trend and some other peaks were very well represented. The model computed several flow peaks in this period responding to the respective precipitation events, such as the peaks in May, October and November 2006. Still the differences with the observed data in May and

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November are noteworthy. According to the local experiences in field, possibly there were some problems about reliability of the discharge observations, particularly during the dry season. This has not been the case with the rainfall observations. Disregarding thus some mismatches during May and November, the Nash-Sutcliffe coefficients were acceptable taking in consideration the simplicity of the model (Table A4).

In order to assess the usefulness of combining rainfall data from raingauges and TRMM as an alternative data for rainfall-runoff modeling, a new hydrological simulation was executed for the Vinces upper catchment. The enlarged station scheme is according to Fig. 5. While the rainfall ground stations daily data series remain unaltered, the new TRMM spots made use of the previously obtained synthetic daily series, corrected from the original satellite data.

This new scheme entailed the recalculation of the average rainfall per subbasin and areas of influence for each station. To achieve a fair semblance, the optimized parameters of the original model were left unchanged. Some worthy comparisons were then achieved (Fig. 7). During some peaks throughout the rainy season of 2006 (e.g. 8 February, 5 March, and others), the newly fed model showed higher streamflow values compared to the ground-based data model. Given the previous underestimation of the original model with respect to the observations, this might have implied a sort of improvement on the model performance (8–13 %) for the general pattern and some peaks (e.g. the peak of 16 March). However, for other peaks the new model caused a larger error of around 18 %. The Nash-Sutcliffe coefficient for the wet period remained almost the same, from 0.83 to 0.81.

Secondly, for the dry season and with the exception of the aforementioned events of May, June and November, the NSC somewhat increased from 0.98 to 0.99. When those events were included, the new simulation showed no improvement compared to the original model due to the overestimation on the original values with respect to the observations. Finally, as an overall yearly view, the Nash Sutcliffe coefficient slightly decreased from 0.81 to 0.76.

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5 Concluding remarks and further research possibilities

New technologies provide manifold options to complement the conventional rainfall spatial data. In this regard, the use of TRMM data to complement precipitation data from rain gauges for the scarcely gauged Vinces upper catchment was explored.

The spatial distribution of the annual rainfall data from TRMM to some extent showed some similarity to the pattern from the similar data from raingauges. This satellite data showed high bias at monthly time resolution. Bias correction factors were computed and, adopting a simple procedure, were spatially distributed, and were used to improve the TRMM data. The procedure showed an easy yet effective way of correcting the bias of TRMM data at a catchment scale.

By making use of the rainfall time series from raingauges the bias-corrected monthly TRMM data were disaggregated to a daily resolution. The temporal disaggregation procedure, albeit simple, could generate corrected daily series close in magnitude with the daily rainfall data from raingauges.

The hydrological model across the upper Vinces catchment successfully exhibited very comparable results with the original simulation. Results at several locations, e.g. at the Baba, Toachi, Pilalo catchment outlets and at the *Quevedo at Quevedo* river station were compared with the river discharge observations and found to be reasonably acceptable. The response the model to the precipitation input was explainable. In general, the differences between simulated and observed runoff happened mainly in May and November (during the dry season) probably as a consequence of localized stormy events in the Andes.

Ultimately, the corrected TRMM data were employed in addition to the existent raingauge measurements as complementary data sources for the rainfall-runoff representation. In spite of some slight overall reductions on the Nash-Sutcliffe coefficient, possibly due to the empirical temporal disaggregation, this new simulation showed outcomes very comparable with those using only raingauge information. Although the new model's results did not improve remarkably, the contribution of this approach was based

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on the fact that given a known bias, the satellite data could still be corrected and may resemble the information provided by the raingauges. Therefore, the TRMM information provided an enlarged spatial characterization on the scarcely gauged area; in this case, the Andean foothills region. The methodology might also be applied to fill-in any missing data in rainfall time series from raingauges by satellite-based rainfall estimates. The availability of many products similar to the TRMM data suggests a high possibility for this task.

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Table 1. Bias correction, TRMM vs. ground data, annual rainfall based on monthly correction.

Validating stations	Ground data Annual rainfall	Uncorrected TRMM Annual rainfall	Uncorrected TRMM Rel. bias (%)	Uncorrected TRMM RMSE (mm yr^{-1})	Monthly bias corrector	R^2	Corrected TRMM Annual rainfall	Corrected TRMM Rel. bias (%)	Corrected TRMM RMSE (mm yr^{-1})
Puerto ila	2578.1	757.6	70.6	206.4	3.15	0.92	2389.1	7.3	56.7
San Juan La Maná	2805.8	600.0	78.6	256.0	4.28	0.89	2571.0	8.4	76.4
Pichilingue	1858.3	595.0	68.0	149.6	4.29	0.85	1654.5	11.0	63.2
Murucumba	1738.9	693.0	60.1	125.3	2.18	0.87	1508.3	13.3	57.3
Pilaló	1095.1	565.5	48.4	60.3	1.85	0.73	1045.5	4.5	34.5
Chiriboga	4653.7	759.3	83.7	356.7	5.66	0.63	4295.6	7.7	108.3
Puerto Limón	2527.5	839.9	66.8	184.4	2.56	0.78	2151.3	14.9	86.8
Unión 71	1983.6	769.1	61.2	141.1	2.25	0.82	1728.0	12.9	69.2
La Cancha	1730.8	678.3	60.8	125.6	2.18	0.75	1481.5	14.4	71.9
La Palizada	1805.8	577.6	68.0	150.6	2.87	0.87	1657.0	8.2	58.2
El Corazón	2391.1	509.2	78.7	217.5	4.47	0.83	2274.1	4.9	77.5

Table A1. Surface water variables for the Vinces River model in HEC-HMS.

Subbasin	Area (km^2)	Constant loss rate (phi) ($mm\,h^{-1}$)	% Imperviousness	Lag time (min)
Baba	925.2	3.6	4.1	1700
Toachi	504.8	3.1	4.5	1407
San Pablo Quevedo	1290.3	4.0	5.8	1507
Pilalo	212.9	2.8	4.7	1186
San Pablo La Mana	190.0	3.3	3.8	1507
Lulu	293.4	4.3	5.3	1326

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Table A2. Baseflow parameters for the Vinces River model in HEC-HMS.

Subbasin	Initial discharge ($m^3 s^{-1}$)	Recession constant	Ratio to peak
Baba	25.5	0.79	0.78
Toachi	1.8	0.79	0.76
San Pablo Quevedo	6.3	0.85	0.67
Pilalo	1.0	0.95	0.85
San Pablo La Mana	4.3	0.76	0.65
Lulu	2.6	0.93	0.70

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Table A3. Gage weights for San Pablo-Quevedo subbasin in the Vinces' upper catchment model.

Gage name	Weight
Immoriec Vergel	0.31
Pichilingue	0.05
Pilalo	0.22
Puerto ila	0.00
San Antonio Delta Plate	0.30
San Juan La Lana	0.10
Union 71	0.02

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Table A4. Nash-Sutcliffe values for some subbasins after the Vinces HMS model.

Subbasin	Nash-Sutcliffe coefficient
Toachi	0.69
Baba	0.67
Pilalo	0.84
San Pablo Quevedo	0.81

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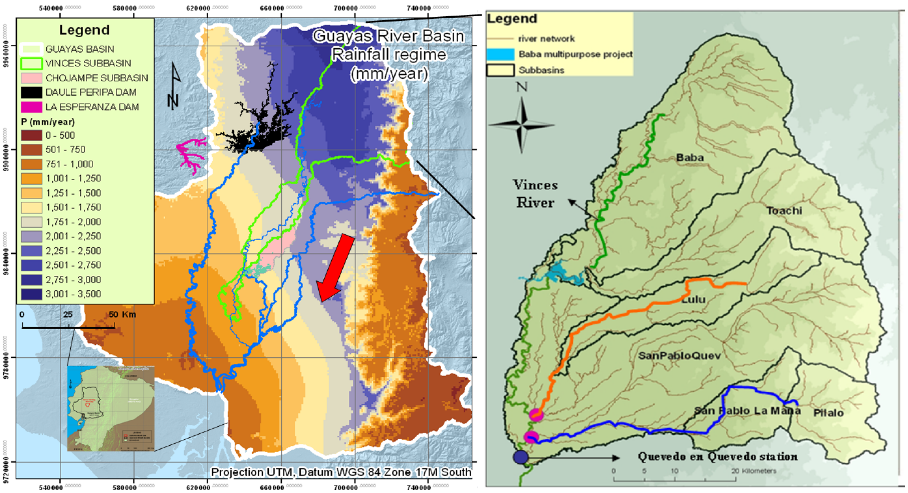

Fig. 1. (a) Left: Guayas River Basin, system flow direction (arrow) and main features; **(b)** right: hydrological model schematization for the Vinces upper catchment (Baba dam project on the west).

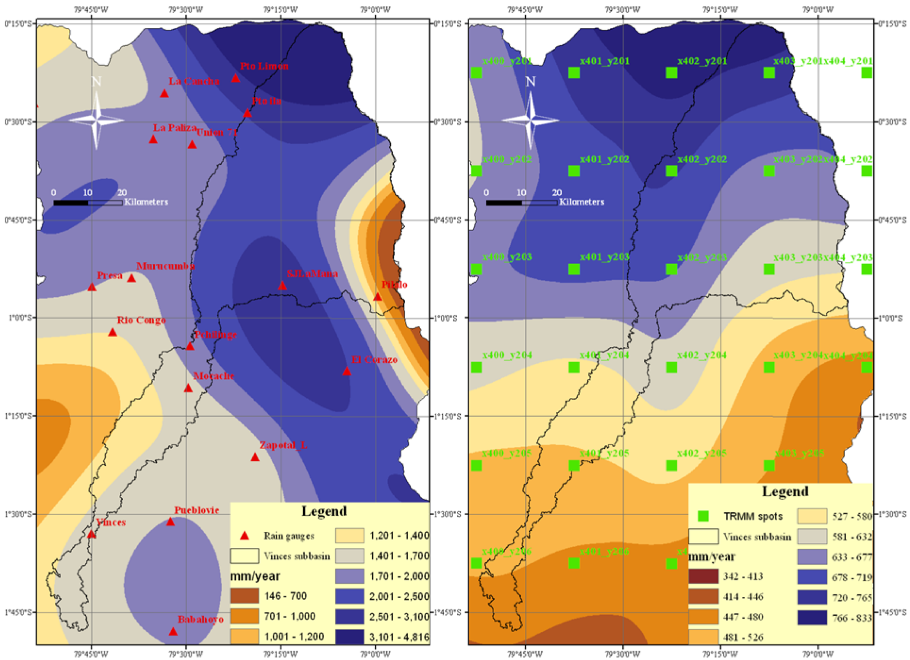

Fig. 2. Annual average rain field comparison between: **(a)** ground stations (left); and **(b)** TRMM data (right), during 1999–2006.

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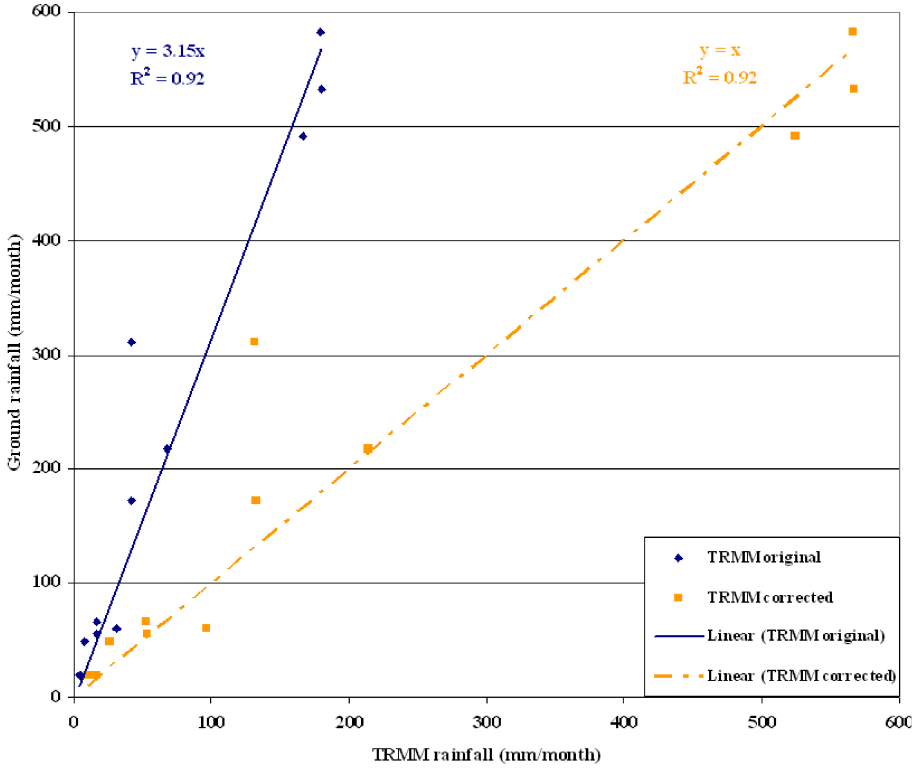

Fig. 3. Bias correction at a monthly scale. Puerto ila station.

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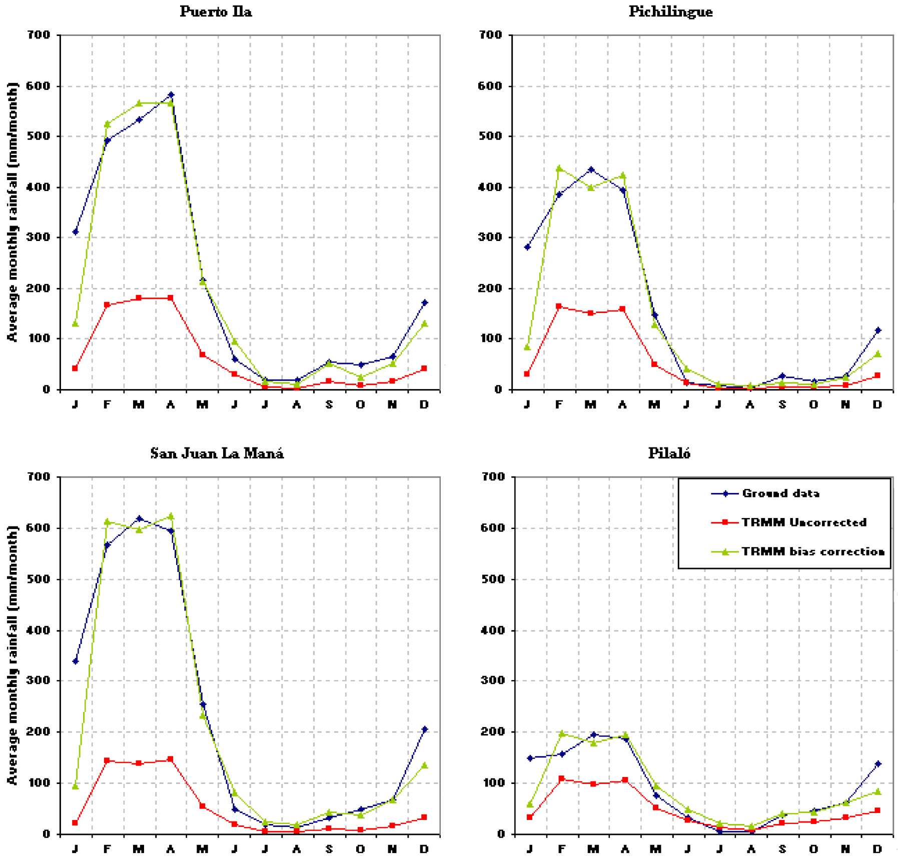

Fig. 4. Average monthly bias corrected TRMM data over 1999–2006 compared with rain gauges and uncorrected TRMM data.

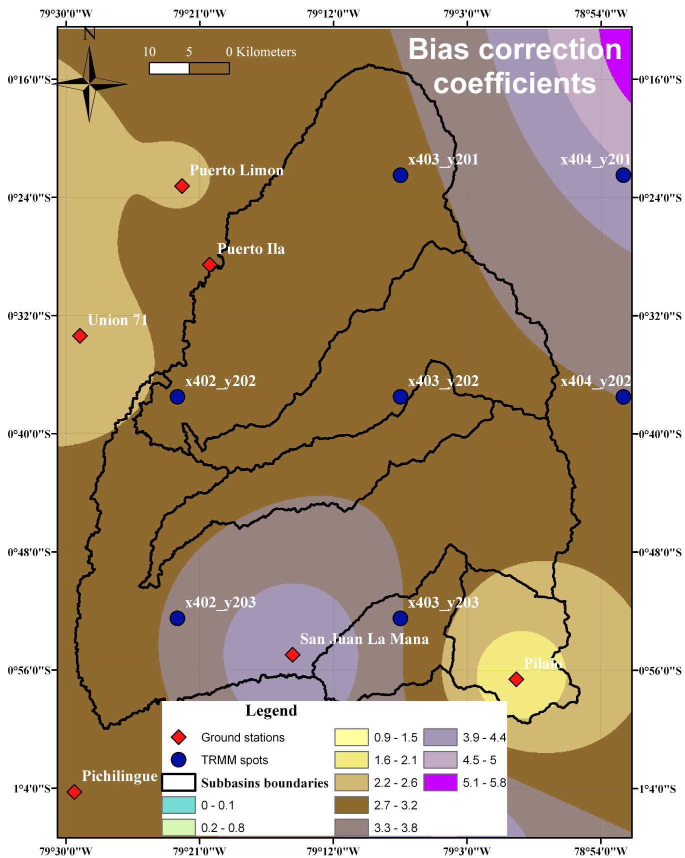

Fig. 5. Spatial distribution of bias corrector coefficients at monthly scale. Vinces upper catchment.

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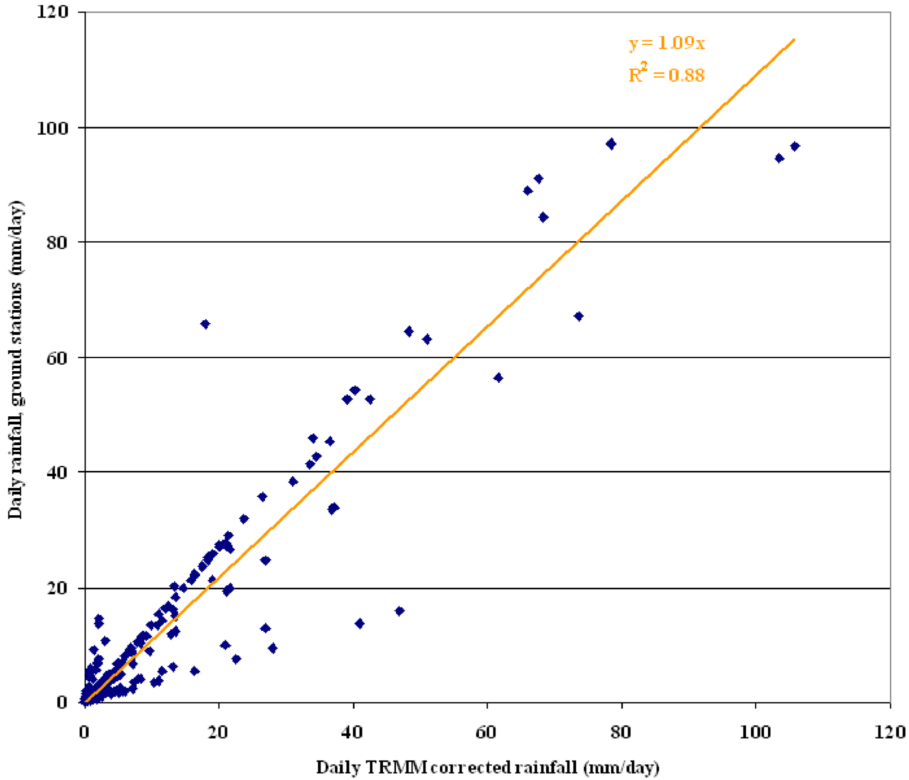

Fig. 6. Comparison of rainfall data from gauges and TRMM corrected data, at daily scale. Puerto ila station.

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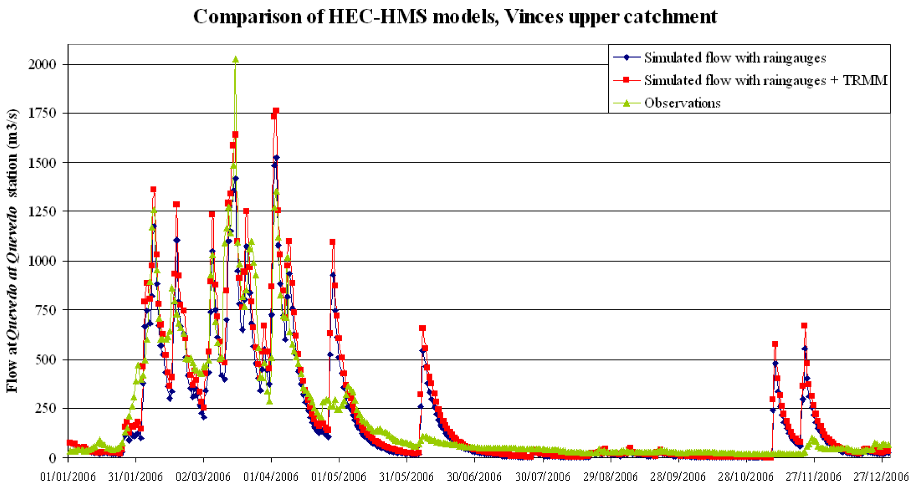

Fig. 7. Rainfall-runoff simulations with different sorts of precipitation data, Vinces River upper catchment.

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