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IMPACT OF CLIMATE VARIABILITY ON FLOW AND SEDIMENT TRANSPORT OF THE MAGDALENA RIVER THROUGH THE ANALYSIS OF HISTORICAL SERIES

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Abstract: The Colombian Hydrological, Meteorological and Environmental Science Institute (IDEAM) highlights that Colombia is susceptible to be impacted by the effects of climate change. Current trends show that the hydrological conditions of various catchment basins are being affected. The Magdalena river basin has experienced an upsurge in erosion processes. This is the largest river artery and the most important in Colombia. The river runs approximately 15 km along the urban perimeter of La Dorada (Caldas) township where dynamic erosion and sediment transport processes can readily be observed. This study focused on the analysis of historical hydrological series in the region, seeking to correlate flow data, sediment bed transport and suspended concentration with the NOAA indexes allowing one to quantify the sediment transport processes that may occur over periods of extreme climatic events (i.e. El Niño and La Niña). Through a field campaign, bed and suspended sediment transport was quantified and considered in relation to river discharge, such data was then analyzed against available historical series over the last 40 years. The results allow one to infer the validity of various NOAA indexes as long term indicators considering the most favorable and unfavorable climate change scenarios and its consequence in terms of predicted sediment transport for the river. Series analysis showed that the BEST and MEI indexes have a higher incidence on the variables analyzed, with a significant correlation from 20% up to 53%.

1 INTRODUCTION

Over the last decades, Colombia has observed an increase in the magnitude and frequency of extreme climatic events and the Magdalena River catchment basin has seen a steady increase in precipitation over the years. Recently a number of anomalies in rainfall events have occurred and are being more recurrent, impacting populations and productive sectors of Colombia (Hurtado, 2010). Figure 1a and figure 1b show the disastrous effect of such extreme events as observed in La Dorada, Caldas.

Figure 1a. Extreme weather events during El Niño, (La Patria, Jan. 2016).

Figure 1b. Extreme weather event during La Niña, Yara. F., Apr. 2017.

La Dorada is located midway upriver along a sharp curve of the Magdalena. The city is situated in a wide valley amongst the central mountain range of the Andes at 178 meters above mean sea level with a population of 76 574 inhabitants as of 2005 (DANE, 2015). The meander located in this area is limited in its width by a geological formation which restricts its evolution. Secondary flow processes are actively deteriorating the outer curve of the river bank producing significant erosion and deposition.

Over the years the city limit has expanded significantly with limited urban planning and zoning restrictions being imposed. As a consequence impoverished neighborhoods have reached the river embankments and with 15 km of the urban perimeter exposed to the channel, the situation has reached a breaking point, exposing housing, public and private property to imminent tumbling or collapse and threatening the local population. Also, intense precipitation has caused flooding and has affected local neighbourhoods aggravating the situation. Figure 2 illustrates the general urban area and city limits.

Figure 2. Bing Maps 2018. Meander of the Magdalena River in La Dorada – Caldas.

The catastrophic events of November and April 2011 are exemplary of how the situation has deteriorated over time. On such occasion, precipitation intensity exceeded any historical previously recorded rainfall in the country and the limited mitigation measures that had been implemented collapsed under pressure.

The level of the Magdalena River exceeded historic flow on record with 6509 m^3/s registered. The event affected 10 neighborhoods and nearly 4000 families. Overall 750 houses were damaged, of which 150 were totally destroyed. In addition, 918 people were evacuated to temporary shelters. (El Tiempo.com newspaper, 2011). The municipality did not have flood drainage canals or levees to evacuate the waters to lower areas. Furthermore, as 5 kilometers of the river embankment was exposed to erosion and scour, the flooding was further aggravated.

Internationally different statistical techniques have been used to establish multivariable correlations to determine the relationship between the ENSO phenomenon and the discharge of a catchment basin (Martelo, 2003).

The effect of the extreme phases of the ENSO (El Niño and La Niña) in a region depend on the time of year, affecting the climate over a whole region and impacting in particular, the magnitude and components of the hydrological cycle (Bedoya et al, 2010). The consequences of such events is a function of the conditions of vulnerability of the considered area. In the case of Colombia, its geographic position in the Andean zone results in a distinct bimodal behavior, with two rain and dry periods during the year (Inzunza, 2001).

In order to better understand the characteristics of flood events in relation to historical data and current climate change scenarios, a formal hydrological event series correlation analysis was undertaken.

2 METHODOLOGY

2.1 Data Series

Historical data series for the region were analyzed using the IDEAM (*Instituto de Hidrología, Meteorología y Estudios Ambientales*) gauge station #23037010 Puerto Salgar - La Dorada, that monitors channel discharge, water depth as well as suspended sediment transport. The following annual data series have been analyzed:

- Daily average discharge 1946 – 2015 excluding 1958 and 1980.
- Monthly average discharge 1946 – 2014, excluding 1958.
- Maximum monthly discharge 1946 – 2014, excluding 1958 and 1980.
- Minimum Monthly discharge 1946 – 2014, excluding 1958 and 1980.
- Daily average waterline 1960 – 2014, excluding 1980.
- Monthly average waterline 1960 – 2014.
- Maximum monthly waterline 1960 – 2014.
- Minimum monthly waterline 1960 – 2014.
- Total transport 1946 – 2015.
- Suspended solid discharge 1946 – 2015.

2.2 Treatment of the data series

A qualitative and quantitative analysis using different estimation time windows was completed on the historical series with a view to classify and organized the recorded data.

The series were examined in relation to the climate series of the National Oceanic and Atmospheric Administration (NOAA) which include: the ONI index, the BEST index, the MEI index and finally the SOI index, establishing the various correlation with the related variables of the Magdalena River in La Dorada – Caldas. The analysis was performed using the Southern Oscillation index for El Niño (ENSO) and the R^2 coefficient.

The analysis strived to determine the best correlation index that can be related to historical discharge data. This variable generally allows for higher correlation values being a persistent variable in hydrology. The data series were smoothed using a mobile average over 3 months to filter higher frequencies, before establishing correlation values.

3 RESULTS

The correlation analysis was completed based on the following consideration (Trenberth, 2001):

El Niño: characterised by an ONI positive value, greater or equal to +0.5ºC

La Niña: characterised by an ONI negative value, smaller or equal to -0.5ºC

3.1 ONI Index

Figure 3a presents the ONI index results as they relate to channel flow over time. One can observe that positive sharp rise of the index match reported El Niño events, in the same way as negative spikes or sharp decline of the index are associated with reported La Niña events in the area with intense rainfall.

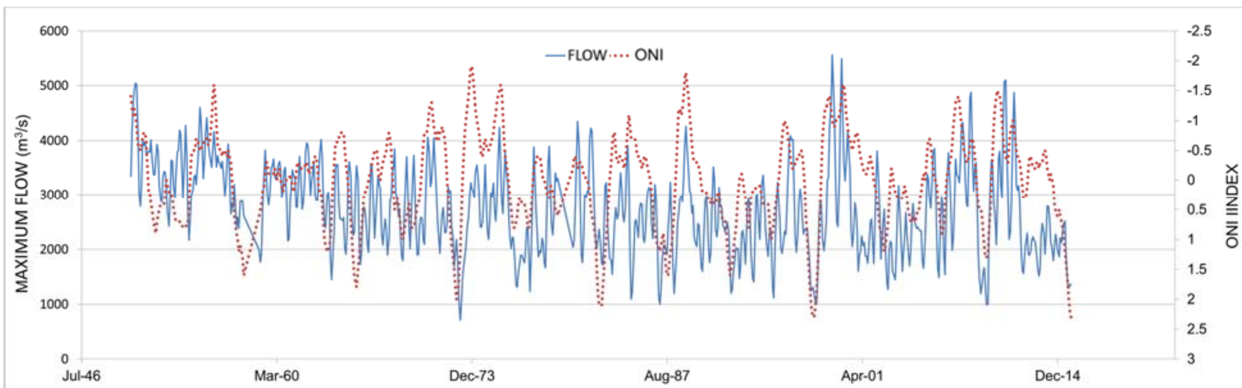

Figure 3a. Maximum discharge correlation to ONI index

The best correlation was found to be 48% for a time window estimate of 3 months, which tends to indicate that maximum flow discharge is related to the information as provided by the ONI index, i.e. the surface temperature of the ocean recorded in the equatorial Pacific Ocean 5 ° N-5 ° S, 170 ° W - 120 ° W, (known as El Niño 3.4) (Tootle, 2008).

The higher correlation between the ONI index and flow indicates that the behavior of the latter in the area, is mostly influenced by the extreme events of El Nino and La Nina. This is partly due to the fact that the registered flows depend on the contributions of the tributary sub-basins to the Magdalena River. As evidenced in figure 3a, La Nina events tend to develop in the months of March and April, presenting the highest intensities in October and November. El Niño events tend to develop in the period of May and June, reaching its maximum level during the period of December and February. (Poveda et al, 2001).

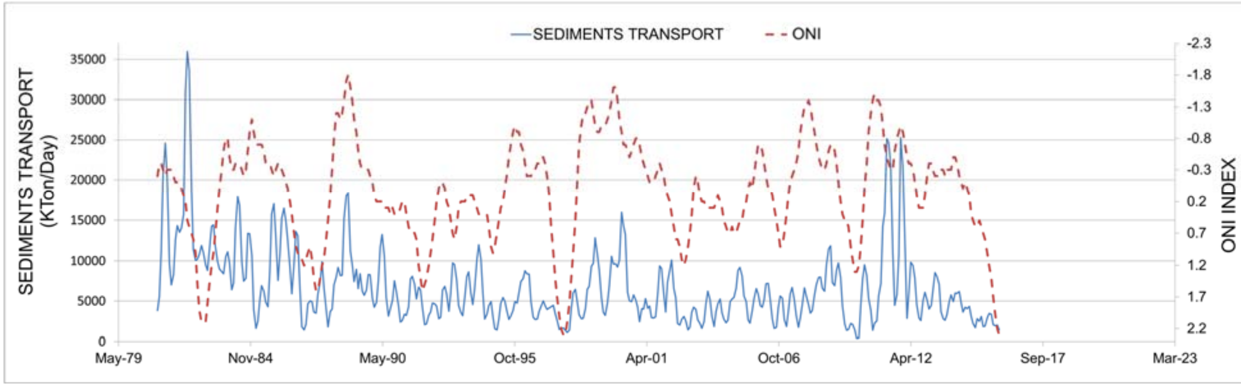

Figure 3b. Sediments transport correlation to ONI index.

In the case of sediment transport (Figure 3b), the correlation with the ONI index is low, averaging approximately 27%, this can be attributed to the number of variables that are involved and affect the transport process. In addition, it was observed that sediment transport presents the least number of months that are significantly related to the index.

3.2 BEST Index

The BEST index combines the SOI index with given temperature at sea level for the El Niño 3.4 (SST) region (Yan, 2011). Figure 4a presents the BEST index results as they relate to channel flow over time. Here positive values can be associated with El Niño events, while negative values can be related to La Niña. The BEST index with 51% over a 2 month estimation time window presents the highest correlation that this index was able to determine. One has to recall that the available data series was provided monthly were the BEST index is determined as a monthly and trimestral average which tend to display a better representation of the phenomena.

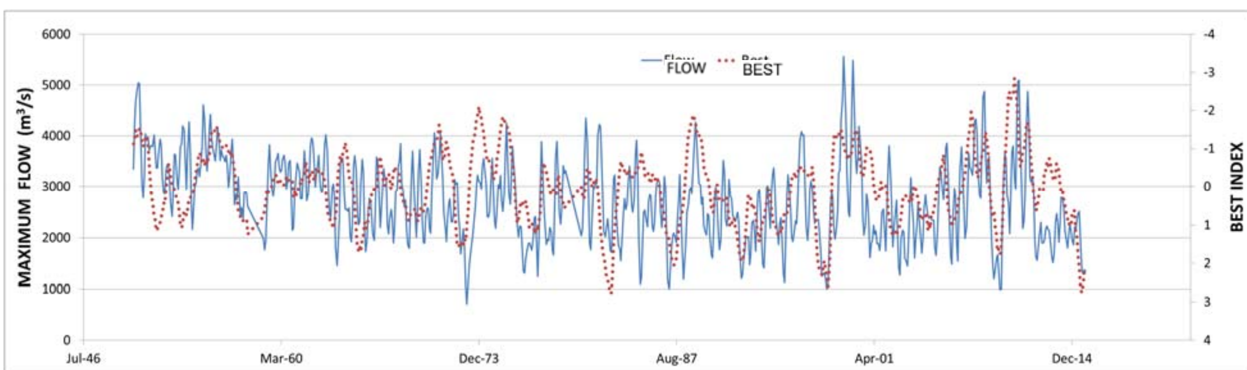

Figure 4a. Maximum discharge correlation to BEST index

For this particular case, there are substantially more months (analysis over a two-month estimate) where the historical series for flow correlates with the BEST index contrasting with the ONI index mentioned previously. Again, La Nina events tend to develop in March and April, and present the highest intensities in October and November. El Niño events tend to develop over the period May and June and reaching its maximum level during the months of December and February.

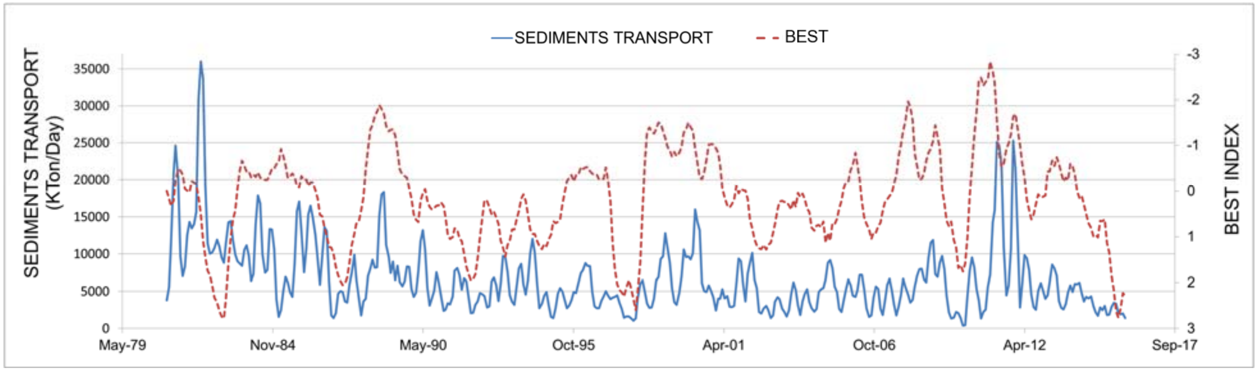

Figure 3b. Sediments transport correlation to BEST index.

Considering Figure 4b, sediment transport is related to the index with calculated correlation of approximately 30%. It may be inferred that sediment transport is influenced by an increase in river stage and increased discharge. In the case of the Magdalena River, the series indicate that the months of March-April and October-November are historically rainy periods, which may explain why the correlation of this variable appears greater during these time periods. It was evidenced that a time window estimate over 3 months of the BEST index shows a greater correlation with extreme El Niño and La Niña events.

3.3 MEI Index

Figure 5a presents the MEI index results. The best correlation encountered between discharge and the MEI index was found to be 49 % considering a 3 month time window. The MEI index is determined considering six monitored main variables of the Pacific tropics including: atmospheric pressure at sea level, zone and meridian components of the surface wind, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky (Wolter, 1987).

In this case, the greatest correlations were obtained relating the MEI index with the minimum and average flow, with 52% and 53% respectively. Furthermore it was observed that peak correlation were in better agreement with the La Niña events. In general, the best correlation values were obtained using estimation over 1 and 3 month time period.

Data analysis indicate that in the case of El Niño, the MEI index was not significantly correlated to the analyzed variables contrary to what was observed with La Niña events.

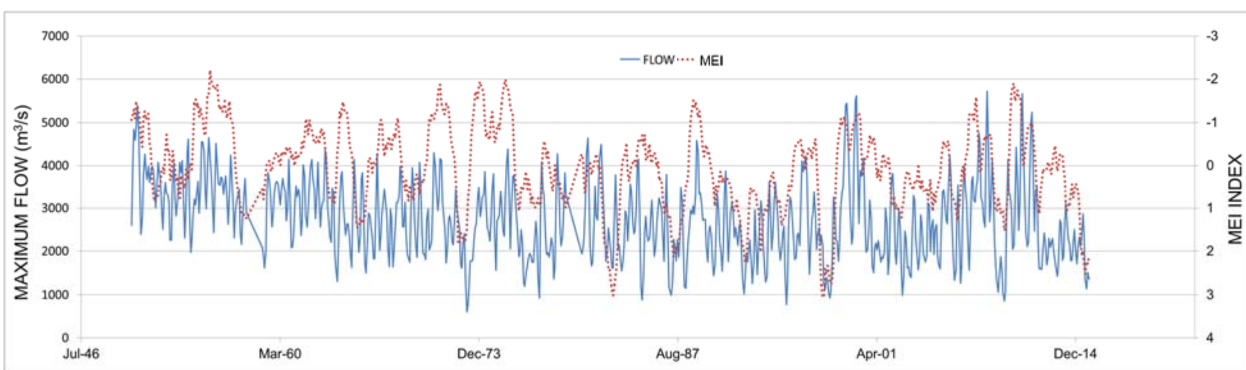

Figure 4a. Maximum discharge correlation to MEI index

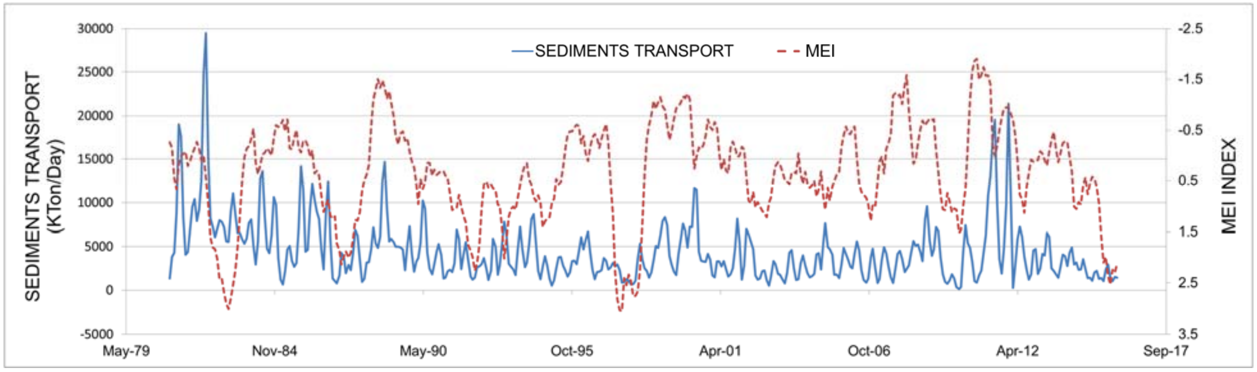

Figure 5b. Sediments transport correlation to MEI index.

Sediments transport analysis for the MEI index (Figure 5b), determined a 27% correlation. As sediment transport is influenced by an increase in discharge, the MEI index displayed specific peaks during the rainy period of March-April and October-November, as was also observed with the BEST index previously.

3.4 SOI Index

In the case of the SOI index, the best correlation was found to be 33% for a 2 month time window estimate as it relates to maximum discharge. The SOI index relates observed abnormalities between mean monthly pressure found in Tahiti (French Polynesia) and Darwin (Northern Australia), (INOCAR, 2001). Figure 6a illustrates the maximum discharge to SOI index results.

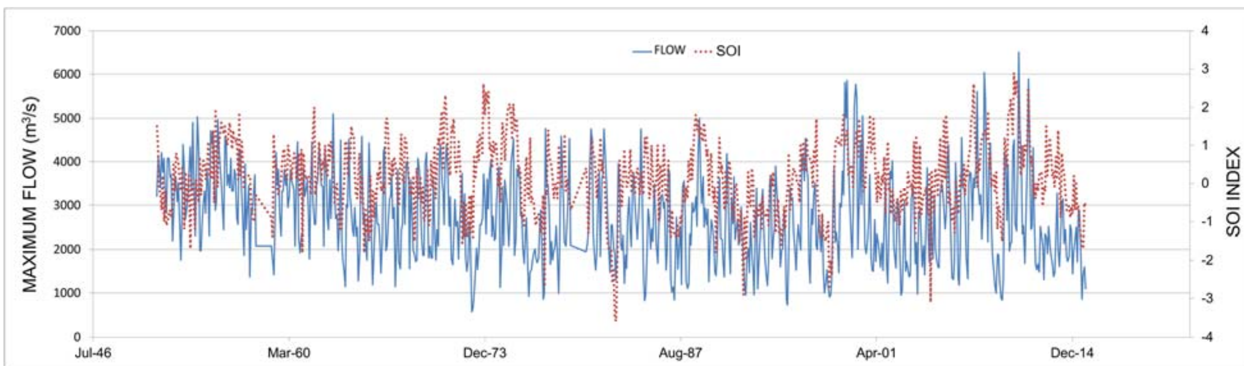

Figure 6a. Maximum discharge correlation to SOI index

It may be suggested that the SOI index displays poor correlation values as it is determined monthly whereas other indexes are generally evaluated over a two or three-month period.

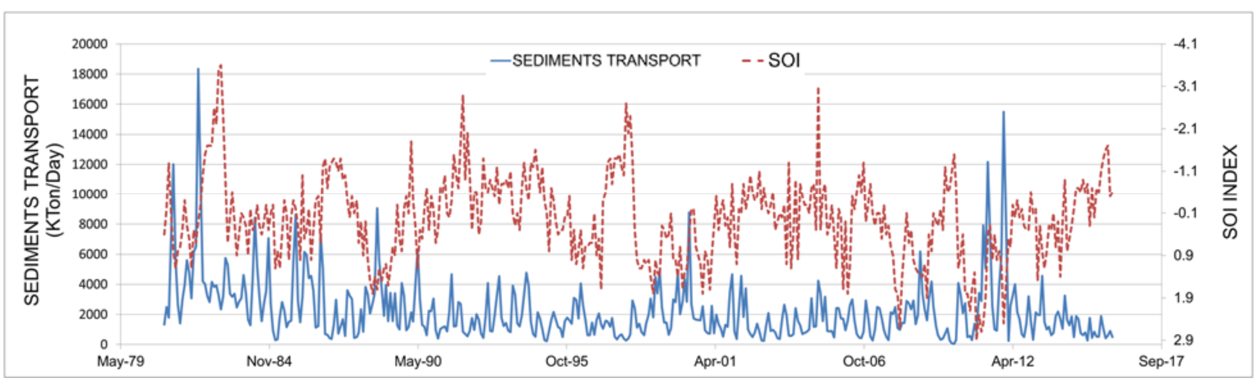

Figure 6b. Sediments transport correlation to SOI index.

In the case of sediment transport (Figure 6b), the correlation is low, averaging approximately 19%. Again, as the SOI index is determined through a monthly average this may explain the lower correlation values in this case. As the data series are considered for a similar time window estimate a greater correlation variability is to be expected.

4 ANALYSIS

The overall results of the various indexes are presented and compared in table 1, illustrating the maximum correlation obtained using the Pearson product moment correlation coefficient of the data series. The latter being interpreted as the proportion of the variance of one variable attributable to the variance of the other.

Table 1. Maximum correlation for each studied variable

MAXIMUM CORRELATION (%)					Time Window for Max. Correlation (Month)
PARAMETER	ONI	BEST	MEI	SOI	
Suspended Solids Tpt. (Kg/m^3)	-23.15	-20.25	-20.65	12.46	3
Bed Tpt. (Kton/Day)	-27.41	-30.13	-27.01	19.02	3
Level min (m)	-43.52	-42.27	-39.31	30.74	2
Level mean (m)	-47.27	-46.56	-42.49	33.4	2
Level max (m)	-47.74	-47.33	-42.81	32.37	2
Flow min (m^3/s)	-43.24	-48.83	-52.31	34.45	3
Flow mean (m^3/s)	-47.05	-52.03	-52.78	35.32	3
Flow max (m^3/s)	-48.34	-51.28	-49.07	33.37	2

The MEI index provided the best results of the analysis with a 52% and 53% correlation to minimum and mean discharge respectively. Nonetheless the BEST index was found to be a better indicator of sediment transport with a 30% correlation factor.

5 CONCLUSIONS

This study has evaluated the historical series available from the IDEAM #23037010 Puerto Salgar gauge station with the NOAA indexes. Generally, the data series related to transport and discharge in relation to evaluated indexes has been found to present a satisfactory fit. Significant correlations have been determined and the persistence of the data has been found to be adequate.

The BEST and MEI indexes showed consistently a higher incidence on the variables analyzed, with a significant correlation coefficient from 20 up to 53%. This would indicate that such indexes are better indicators of hydrometeorological events occurring in the zone. In general, the best correlation results were determined using a 3 month time window estimate. It was also observed that when analyzing the historical series with the NOAA indexes, greater anomalies were observed and lesser predictivity was determined when relating sediment transport to La Niña events.

In all cases, accuracy of the correlation is related to the homogeneity of the available data set. Most historical events related to discharge and sediment transport have shown an acceptable intersect; although little is known of the accuracy of the data provided by the monitoring gauge station, further probabilistic evaluation of the data is limited.

Nonetheless, one can infer that the monitoring station data series would provide for a qualitative and long term planning and management tool relating liquid and solid discharge to reported El Niño and La Niña events in the La Dorada, Caldas region and providing for a better understanding of the hydrological alteration presently occurring in Colombia.

Finally considering the various NOAA indexes (NOAA, 2018) studied, extreme hydrological events resulting from climate change do impact suspended solid and bed transport rates over the months of May and November in particular displaying greater correlation values for the region of La Dorada Caldas.

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