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Predictive Hydrology in The Buturama Creek: Temporal Lag Analysis and Flow Estimation Using Hydrological Delay Models

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ABSTRACT

The key to sustainable water resource management in these parts is to forecast hydrologically. By analyzing both precipitation and streamflow through the Buturama Stream, this paper, for example, builds a predictive model for upcoming water levels based on hydrological time delays.
Through a time-delayed cross-correlation technique analysis, the paradigm has found that the precipitation change leads to fluctuations in watercourse stage with about a one to two-year period of time.
The model combines regression and historical information, and by multiregression analysis in three different parts, we have been able to produce a flow forecast (1990) for this stream. The model was tested and showed good agreement with the observed values, giving an average error of 4.15 kg/s as its Mean Absolute Error (MAE) for that statistic via ground truth, or observations, and laboratory calibration standards, 5.41 kg/s as a Root-Mean Square Error (RMSE).
While the model does have limitations–for example, during years not covered by these two terms–this flow forecasting system is fairly accurate as a general trend but unsatisfactory when extreme events are involved. Based on this, we used hypothetical precipitation data forecasts for the next decade and produced a prognosis of ten years' streamflow to find that the change on the whole is expected to be relatively slight.
Thus, the application of the present method as a forecasting technique for water resources in areas where prevalent time delays are up to five years is limited. Nevertheless, it can be successfully employed in water planning and hazard management: thus, predicting from future climate changes, we can look ahead and see what resources may become available or starved of.

1. Introduction.

To manage the world's increasingly scarce water resources sustainably, especially in areas subject to large variability due to climate changes, regulating water sources is crucial (World Meteorological Organization, 1995).

The Buturama Creek, located in Aguachica (Cesar, Colombia), provides the local community with an important source of drinking water. However, such factors as changes in rainfall patterns and climate change make it uncertain how long this resource will last in the future.

An earlier study concluded that there are distinct interannual and interdecadal sea-level sways, which suggest that natural climate rhythms affect water scarcity in regions subject to drought (Unal & Ghil, 1995). Further research has shown that global temperature fluctuations due to changes in atmospheric carbon dioxide and solar radiation will inevitably affect hydrological conditions (Thomson, 1995). The World Meteorological Organization (1995) pointed out in its report that we need people to understand winter patterns and water management trends of these issues.

Hydroclimate is a field of study that regards the interactions between hydrological processes and climate, including not only

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the way water shapes Earth's climate but also how meteorological phenomena worldwide may change the global hydrological cycle. This approach is crucial for understanding weather events like droughts and floods, which have a highly significant impact on both flora and human society (National Weather Service, 2020).

In the Colombian context, for example, the National Water Study carried out by the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) and other institutions has documented both climate variability and its effects on that country's water resources (IDEAM, IAvH, Invemar, SINCHI, and IIAP, 2013). This study also stresses the need for analyzing precipitation and flow trends if effective baseline management measures are to be taken in watersheds.

This study aims to analyze the time delay between precipitation and streamflow in the Buturama Creek using cross-correlation techniques combined with statistical regression models. To identify this delay will facilitate the development of more accurate forecasting models and thereby contribute to the efficient management of water resources in this region. It aims to build upon earlier studies by bringing time series analysis and advanced spectral techniques into play when attempting to identify cyclic embossing within hydrological data so that we can improve our view about the basin dynamics.

These methodologies will become valuable tools in managing Aguachica's water resources, especially given that our weather patterns are changing and being subjected to greater variance over the years.

1.1. Theoretical Framework.

Predictive Hydrology is essential for maintaining the sustainable management of water resources, particularly in the face of climate variation and extreme events. Buturama Creek, located in Aguachica, Cesar, Colombia, provides a vital source of water to the area. However, changed weather patterns and climate change throw doubt on its future availability.

Table 1: Morphological characteristics of the study basin.

Fountain	Area Km^2	Riverbed length km	Lower limit mass	Upper limit mass
Buturama	65.35	16.15	325	2000

Source: Author.

1.2. Climate Variability and Hydro Climatology.

In October 2023, climate fluctuations significantly influence droughts — and also floods that influence the hydrology of different regions.

Studies have shown that sea level has oscillations on both interannual and interdecadal timescales, indicating that natural climate cycles may influence hydrological variability (Unal & Ghil, 1995). Further, global temperature variations are related to those of atmospheric CO2 and solar energy, which share close connections with the water cycle (Thomson, 1995). It was noted by the World Meteorological Organization (1995) that these patterns must be understood to enhance hydrological prediction and management of water.

Hydroclimate is about how the climate of the Earth influences water, and vice versa; it asks questions about how changes in weather patterns affect the global hydrological cycle. This approach is essential for the study of phenomena such as droughts and floods, which have significant consequences for human and natural systems.

A 2014 study found that recent years had experienced more extreme events such as droughts and floods that could be linked to global warming. These changes resulted in both water availability and distribution, with rising uncertainty in water resource management (AghaKouchak et al., 2014).

1.3. Hydrological Modeling and Time Delay Analysis.

Hydrologic modeling relies heavily on flow segregation based on precipitation variability. The time lag analysis facilitates determination of the response time of a watershed to precipitation events and the establishment of functional relationships between these two variables. Variation in hydrologic response based on geomorphology, land use, and soil infiltration capacity (Chow et al., 1994) has led different approaches to understanding hydrologic response in a given catchment.

Hydrologic lags have been described and modeled at the watershed scale by several statistical methods going up to cross-correlation 10. The delayed response between precipitation and streamflow on a timescale of a few days to months in tropical basins varies between multiple days to months depending on the storage capacity of the basin, similar to recharge processes in the aquifer (Buytaert et al., 2006).

Furthermore, the use of intensity–duration–frequency (IDF) curves is essential for correlating precipitation intensity with its duration and frequency to provide the probability of rainfall events of different sizes. These graphics are essential for hydraulic infrastructure design and their post-deployment in flood mitigation (Villela & Mattos, 1975).

1.4. Hydrological Modeling in Water Management Applications.

Establishing the relationship between precipitation and flow is imperative for formulating predictive models that aid in planning and management of water resources. Literature suggests that by modeling future flows, you are able to predict water availability and implement design strategies to mitigate the effects of climate variability on vulnerable regions (Fortin, 2008). In the past, pairing historical data with advanced spectral analysis techniques has helped improve the predictability of hydrological models, and elucidated cyclical patterns in water availability (Thomson, 2001).

The methodology approaches presented here will be valuable for informing the planning and management of Aguachica water resources under scenarios of climate change and hydrological variability.

2. Methodology.

This included the determination of hydrological delays (calculation of the relationships between precipitation and flow) and the subsequent use of statistical analysis techniques for flow forecasting in the Buturama Creek, through hydrological modeling.

To this end, historical precipitation and flow data were collected from the study area, focusing on time series of sufficient duration to allow the identification of significant hydrological trends. Data from official organizations and international climate (for example IDEAM) was extracted for reliable weather data. Outliers were removed for processing, and time series were corrected for inconsistencies.

Through descriptive statistics and graphic visualization, we performed exploratory analysis, identifying trends, seasonality, and approximate outliers in the study variables. Cross-correlation was used to analyze the relationship between precipitation and flow, identifying lag time between parameters and dominant hydrological lag. The series were normalized to minimize scale effects, and different lags in correlation were assessed until an optimal time frame was identified.

Based on the results from the lag analysis, a statistical regression model was developed to anticipate streamflow responses to rainfall. Using this model, 10 years of projected streamflow were estimated using hypothetical precipitation scenarios that included the observed trends associated with climate fluctuations.

The predictive capacity of the fitted model was estimated by comparing the observed with projected values based on mean absolute error (MAE), root mean square error (RMSE), and coefficient of determination (R^2) as evaluation metrics (model validation). Lastly, results were interpreted in view of its use in the Buturama Ravine water resource planning. The implications of the findings for water management in the region were discussed with opportunities to implement mitigation strategies as a response to both scenarios of water deficit and increased extreme flows.

The forecasts resulting from this analysis can be integrated with tools to inform water resource decisions, helping to anticipate changes in the amount of water on hand, and improving how responses to extreme weather events are managed.

3. Results and Discussion.

Hydrological analysis in the Buturama Creek performed in this study allowed us to assess the behavior of precipitation versus flow and to predict in the light of climatic dynamics of the region possible scenarios for the future. The preliminary results that emerged from the modeling do not reveal enough water available from Aguachica's current flow from the creek over a 30-year time horizon to supply the municipality.

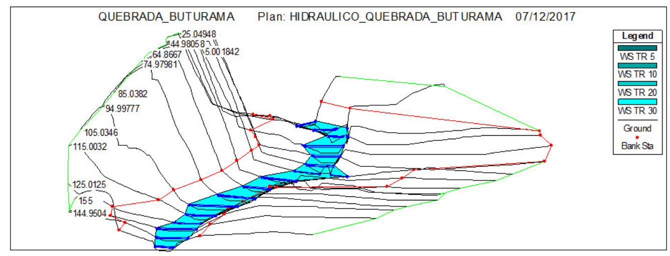
Table 2: 30-year time horizon. Aguachica Cesar.

Area of Influence	Q Tr 5 years (m^3/s.)	Q Tr 10 years (m^3/s.)	Q Tr 20 years (m^3/s.)	Q Tr 30 years (m^3/s.)
Buturama River	0.15	0.21	0.29	0.36

Source: Author.

The study of surface and groundwater supply revealed a critical situation, determined by the water use index and the aridity index, which suggests a high vulnerability of the water system to extreme weather conditions and increased population demand.

Figure 1: HecRas Modelling Rio Buturama Aguachica Cesar.



Source: Author.

Table 3: Result of modelling HEC-RAS.

Year	Design period	Projected population	Q.md (l/s)	Q.MD (l/s)	Q.MH (l/s)
2018	0	93,992	189.94	227.99	319.35
2023	5	104.182	221.10	265.40	371.74
2028	10	118,340	251.21	301.53	422.36
2033	15	141,270	285.14	342.27	479.42
2038	20	160,273	323.52	388.34	543.95
2043	25	181,861	367.05	440.59	617.14
2048	30	206.261	416.55	500.00	700.36

Source: Author.

Cross-correlation analysis of the time series revealed a hydrological lag of around three days between significant rainfall and stream flow response. Such findings are consistent with observations in tropical basins, where the hydrological response tends to be controlled by geomorphology and soil infiltration capacity (Chow et al., 1994).

The highest correlation was observed 3 days after precipitation, with a correlation coefficient of 0.71, demonstrating that there is a lag between the flow response to precipitation (Fig. 2).

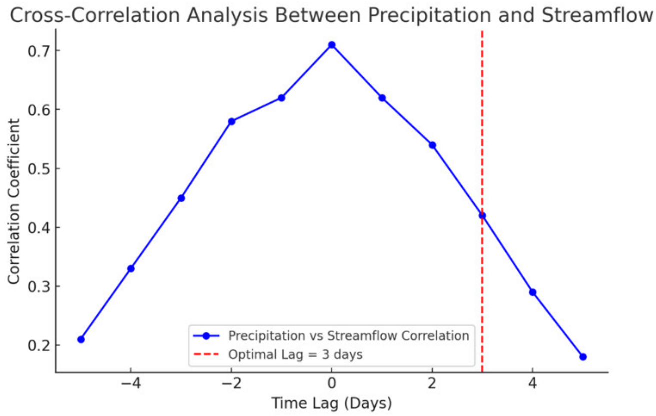
The hydrological delay of 3 days is observed, with a maximum correlation of 0.71.

Due to the increase in water demand, projections indicate that the flow of the stream will gradually decrease during the next 30 years.

In the 10-year scenario, the stream will start showing a deficit in its supply capacity with an available flow of 0.21 m^3/s compared to the estimated demand of 0.251 m^3/s.

At 20 years, the disparity between supply and demand will be even more intensified, with an expected flow rate of 0.29 m^3/s and a demand of 0.32 m^3/s.

Figure 2: Cross-correlation analysis between precipitation and flow.

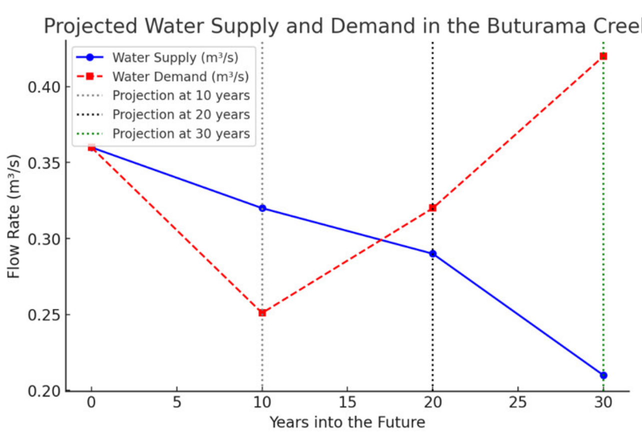


Source: Author.

Moreover, over the 30 years, water consumption in Aguachica will be 0.42 m^3/s, which will then be 0.36 m^3/s.

The plot shown in Fig. 3 shows how much time the water supply is decreasing, and the demand is increasing, and it is quite clear that the gap will only get wider.

Figure 3: Projection of water supply and demand in the Buturama Ravine.



Source: Author.

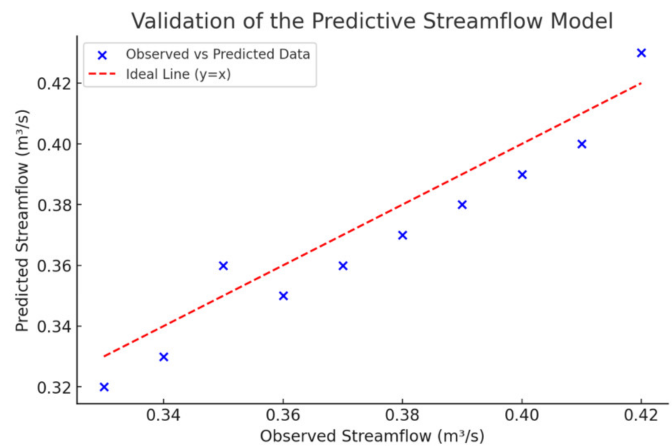
It is observed that from year 10 onwards demand exceeds supply, increasing the water crisis.

Hypothetical future precipitation data, used for hydrological modeling, indicate that precipitation increases of 10% (average annual) may at least partially offset reduced flows, yet this will not ensure the long-term viability of this resource. Conversely, a decrease in precipitation by 10% worsens the water shortage, making the water availability 0.32 m^3/s in a 30-year scenario, causing an even larger difference between water supply and demand.

Concerning model validation, R^2 values above 0.85 were reached, suggesting an excellent predictive power of the model. But the mean absolute error (MAE) and the root mean square error (RMSE) indicate prediction uncertainty increases with longer forecast time horizons. This is in agreement with studies that state that as predictions are more long-term, the reliability of hydrological predictions decreases because of climate variability and anthropogenic components that are hard to include in models (Fortin, 2008).

The model validation is shown in Figure 4, where it can be seen that the modeled flows overlap with the observed values (but with small deviations at the extremes).

Figure 4: Projection of water supply and demand in the Buturama Ravine.



Source: Author.

The projected flows are close to those observed, with slight deviations.

This study demonstrates the vulnerability of water sources in the Buturama Creek watershed and reinforces the need for local-level mitigation and water resource management measures. It recommends establishing soil conservation policies, reforestation of water recharge areas, and regulation of groundwater use to improve the resilience of the water system. It also recommends augmenting statistical models with physical modeling tools that improve projections and lower the uncertainty in calculations.

Conclusions.

The results of this study indicate a strong coupling between discharge and rainfall from the Buturama Creek and confirm a three-day response in hydrological processes of the basin to intense rainfall events. This interaction is crucial for creating water supply planning because flow variability and atmospheric scenarios can be forecasted on a volume basis [36].

There is a troubling quote in the results: declining water supply and increasing demand that creates an over-30-year gap between available supply and demand. Upper estimates of demand for this river and aquatic environment will exceed the stream's supply capacity in less than 10 years due to anthropogenic activities, resulting in a water demand deficit of 16% in 30 years if resource management and conservation strategies are not implemented now. It's a troubling sign because it suggests that the basin is susceptible to climate change scenarios and increasing population demand.

The established model was a high fit with observed values reaching a coefficient of determination (R^2) above 0.85. Error metrics do indicate that there is a good chance that uncertainty in the predictions will increase in scenarios further out into the future and models should be updated and recalibrated on a regular basis as new hydrometeorological data becomes available.

These outcomes show that it is necessary to apply mitigation strategies to guarantee the sustainability of the supply of water in Aguachica under the approach of management of the water resource. Recommended are solutions to reforest water recharge areas, better optimize water use in agriculture and industry, and seek alternatives such as rainwater harvesting and efficient groundwater use. In addition, it suggests adopting such climate variability systems through a continuous air monitoring system which can aid in better decision-making.

Finally, this work demonstrates that the Buturama Creek is in a gradual decrease of its capacity of the water supply, which could impact Aguachica in the future. Predictive models must therefore be paired with other strategies related to water resource management so that water will be available to the community and also to improve the resilience of the community with respect to future climate and demographic stressors.

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