COMPARATIVE ANALYSIS OF ENVIRONMENTAL FLOWS AND ECOLOGICAL FLOWS IN THE CHINCHINA RIVER BASIN, COLOMBIA

Jorge Julián Vélez[1], Olga Ocampo[1-2], Adela Londoño Carvajal[1], Mathew Wahl[1], Diana Carolina Giraldo[1], Elizabeth Sánchez[3]

[1]*Universidad Nacional de Colombia sede Manizales, jjvelezu@unal.edu.co*

[2] *Universidad Autónoma de Manizales*

[3] *Universidad de Caldas*

ABSTRACT

The complexity of water uses represented by hydropower generation, water consumption, agricultural and industrial supply, has created difficulties in estimating ecological and environmental flows. Moreover, different methodologies have been applied for estimating these minimum flows that are essential for the preservation and the conservation of rivers. The ecological flow ensures the conservation of river basin ecosystems; while the environmental flow is supporting the minimum flow, which is required not only for ecosystems but also for the development of economic activities. Hydrological and holistic methods have been proposed in Colombia for ecological and environmental flow estimation. These methodologies were analyzed using a case study in an Andean high mountain basin, The Chinchina River Basin, which is characterized by a bimodal regime and the influence of El Niño Southern Oscillation- ENSO- on the stream flow. The hydrological modeling was used to estimate the water supply and its variability due to the effects of ENSO. Hydrological, hydraulic and habitat criteria were considered in the holistic methods. The study concludes that holistic methods are most appropriate for use in Colombian Andean basins and therefore should be incorporated into comprehensive water resource management plans. However, the discussion on the best methodology is not over in Colombia; therefore, it is mandatory that scientists support government agencies in making informed decisions.

KEYWORDS:
Minimum flows, Ecological flow, Environmental flow, holistic methods, hydrological methods.

INTRODUCTION

As demand for water increases across the globe, the rise is also evident in Colombia, according to the water studies of the Institute of Hydrology, Meteorology and Environmental Studies of Colombia (IDEAM, 2010). Although the country has significant water resources, they have not been evenly distributed, especially in the Andean region where the highest number of human settlements and economic activities is situated. In fact, the water stress in Andean River Basins and increasing conflicts over water use have been caused by the growth in water demand for agriculture, livestock, industry, mining, hydroelectric generation and human consumption (IDEAM, 2008). As a consequence, the availability of minimum flows for ecosystem maintenance is likely to decrease because of water stress.

These minimum flows usually called environmental or ecological flows are critical not only for the provision of ecosystem services, but also to the development of socioeconomic activities. However, there are slight differences between these minimum flows, according to the applied terminology, as follows: The ecological flow is usually referred to as the minimum flow needed to preserve the existing river ecosystems (Ormazabal, 2004). The minimum ecological flow is restricted to low flows during dry seasons in order to sustain life in the river (King et al., 1999; Palau, 2003). The compensating flow is the minimum flow required to ensure the survival of a selected aquatic ecosystem (UNESCO, 2007). The maintenance flow is the flow required to keep the river ecosystem functions, including the aquatic and riparian species; then, it is focused on the conservation of biotic values for the river ecosystem (APROMA, 2000). The conditioning flow is the complement of the previously estimated minimum flows or maintenance flow, it is related to abiotic aspects of fluvial ecosystems as dilution, landscape, recreation, among others (Palau, 2003).

The environmental flow represents: 1) the hydrological regime to maintain the biota of the river jointly with social goods and ecosystem services (Richter et al., 1997); 2) the hydrological regime to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated (Dyson et al., 2003); 3) the amount of water that could be extracted from the river without causing unacceptable levels of ecosystem degradation in the case of severely altered rivers (King and Louwe, 1998); 4) the amount of water needed to restore and rehabilitate river ecosystem to a required state or condition (Palau, 1994); 5) the amount, frequency and quality of water flow required to sustain freshwater ecosystems, estuarine and human welfare that depend on these ecosystems (Brisbane Declaration, 2007).

Colombian Resolution 865 (Ministry of Environment, 2004) defines the ecological flow as the flow required for the preservation of flora and fauna in the river and the maintenance of the natural ecosystems. According to this regulation, the minimum ecological flow must be maintained at different reaches along the river, in order to ensure the conservation of aquatic resources and ecosystems. Otherwise, the environmental flow is defined as the water amount required in terms of quality, quantity, duration and seasonality for the ecosystem sustainability and for the development of socioeconomic activities of users along the stream (Ministry of Environment and Sustainable Development, 2013). The differences between ecological and environmental flows are relevant for decision makers, because they need the best agreement among social, economic and ecological impacts on the river in order to make informed decisions.

Multiple methodologies are used worldwide to estimate these ecological or environmental flows needed to maintain healthy ecosystem rivers (Tharme, 2003, Boodoo et al., 2014). These methodologies could be categorized based on hydrological, hydraulic, habitat and holistic methods as shown in Table 1.

Table 1. Methods for environmental flow estimation in different countries.

Categories	**Methods**
Hydrological	Tennant Method (Tennant, 1976) Flow duration curve analysis (Gordon et al., 1992) Average Base Flow, ABF (USFWS, 1981) Range Variability Method, RVA (Ritcher et al., 1996)
Hydraulic	Wetted perimeter Method (Reiser et al., 1989)
Habitat	Instream Flow Incremental Methodology -IFIM (Gore and Nestler, 1988) Physical Habitat Simulation System -PHABSIM (Nestler et al., 1989)
Holistic	Building Block Method, BBM (King and Tharme, 1994) Holistic method (Tharme, 1996) DRIFT method (Brown and King, 1999). The expert panel assessment method, EPAM (Swales et al., 1994) Ecological Limits of Hydrologic Alteration, ELOHA (Poff et al 2010)

The estimation of hydrological regime is the basis of hydrological methods; it is usually expressed as a fixed percentage of a statistical central tendency, as a percentile of the flow duration curve, or associated with a frequency analysis represented by a return period in years. The hydraulic methods relate hydraulic variables as wetted perimeter, depth and flow velocity with habitat availability for the target species in the ecosystem. The ecological or habitat methods use indicators and habitat integrity indices as a basis for the development of communities and indices of biotic integrity of specific communities as fish, periphyton, macroinvertebrates and riparian vegetation. Finally, holistic approaches relate all these components in the river, using the hydrologic analysis, hydraulic classification, biological data, the economic, social and expert knowledge (Tharme, 2003; Castro et al., 2006; King et al., 2008).

Only the holistic methods take into account the seasonal and interannual variation of flow that occurs in some basins. It is necessary to consider this variation in flow regime within the comprehensive water management plan of Andean basins because of the multiple ecosystem services provided by these basins.

In Colombia different methodologies (IDEAM, 2000; 2004; 2008; 2010; Ministry of Environment, 2004; UN-MAVDT, 2008; Ministry of Environment and Sustainable Development, 2013) have been applied for the estimation of ecological and environmental flows.

The National Water Study (known as ENA in Spanish), (IDEAM, 2000), considered as the minimum stream flow, the multi-annual average flow of minimum 5 years and maximum 10 years remaining 97.5% of the time in the Flow Duration Curve, FDC. The ENA (IDEAM, 2004) estimated the minimum flow and the one remaining 75% of the time in the FDC and the ecological flow as 25% of the lowest monthly multiyear average flow of the current FDC. The Ministry of Environment (2004), according to Resolution 865, proposed that the Environmental Agencies could choose between the above methods according to the information available and the particular regional characteristics.

Subsequently, the ENA (IDEAM, 2008) established a minimum flow, the arithmetic average of the flow rates that exceeded 75% of the time during low flows and considering the 97.5% probability of exceedance of the FDC. The ENA (IDEAM, 2010) determined the environmental flow as the one remaining 85% or 75% of the time in the FDC, depending on the rate of retention and hydrological regulation index- HRI, if greater or less than 0.7.

In 2009, based on studies performed by the National University (UN-MAVDT, 2008), The Ministry of Environment proposed a holistic methodology for the analysis, which considered the hydrological and hydraulic information, water quality and the biotic integrity indexes of fish communities, periphyton, macro invertebrates, and riparian vegetation. The first proposal of environmental monthly flows is the maximum value between 7Q10 and Q95% for the corresponding month and hydrological conditions, which must be adjusted considering the maximum alteration of the FDC, the maximum disturbance frequencies of minimum flow values and the alteration of the hydrological regime due to ENSO, the conceptualization is summarized in Figure 1.

The Ministry of Environment and Sustainable Development (MADS, 2013) considered holistic methodologies as proposed by the ENA (2010) for the definition of environmental flows in environmental licensed projects. Consequently, the environmental flows are the higher values of 7Q10, Q95 and Q75 indexes for each month, considering the wet (Niña years), average (Normal years without ENSO) and dry (Niño years) hydrological condition for 12 months and adjustments based on other criteria to preserve the hydrological regime along the streamflow. Recently, the Ministry of Environment and Sustainable Development proposed another method based on a seed environmental flow, which is estimated using only hydrological FDC, this flow can be modified according to biotic and habitat requirements (INGETEC, 2014).

MATERIALS AND METHODS

The case study is the Chinchiná River Basin, an Andean Basin located in Colombia as shown in Figure 2. Although, it covers an area of only 1052 km², this basin has a great diversity of climates and landscapes for its strong altitudinal gradient from the perpetual snows up to the valleys of the Cauca River. Figure 2 also shows the altitude based on Digital Elevation Model DEM extracted from United States Geological Survey USGS database.

The soils are characterized by volcanic ashes with the presence of geological faults. Tropical rainfall forests could be found in the upper basin and also fragmented throughout the basin. The 55% of the department's population and 80% of economic activities are concentrated in the

Chinchina River Basin (Ocampo, Vélez and Londoño, 2014). With regard to agricultural and livestock activities, citrus plants, coffee and corn crops grow in the lower basin; while coffee and livestock can be found in the middle basin, and cattle and potato crops in the upper basin (Ocampo, Vélez and Londoño, 2014).

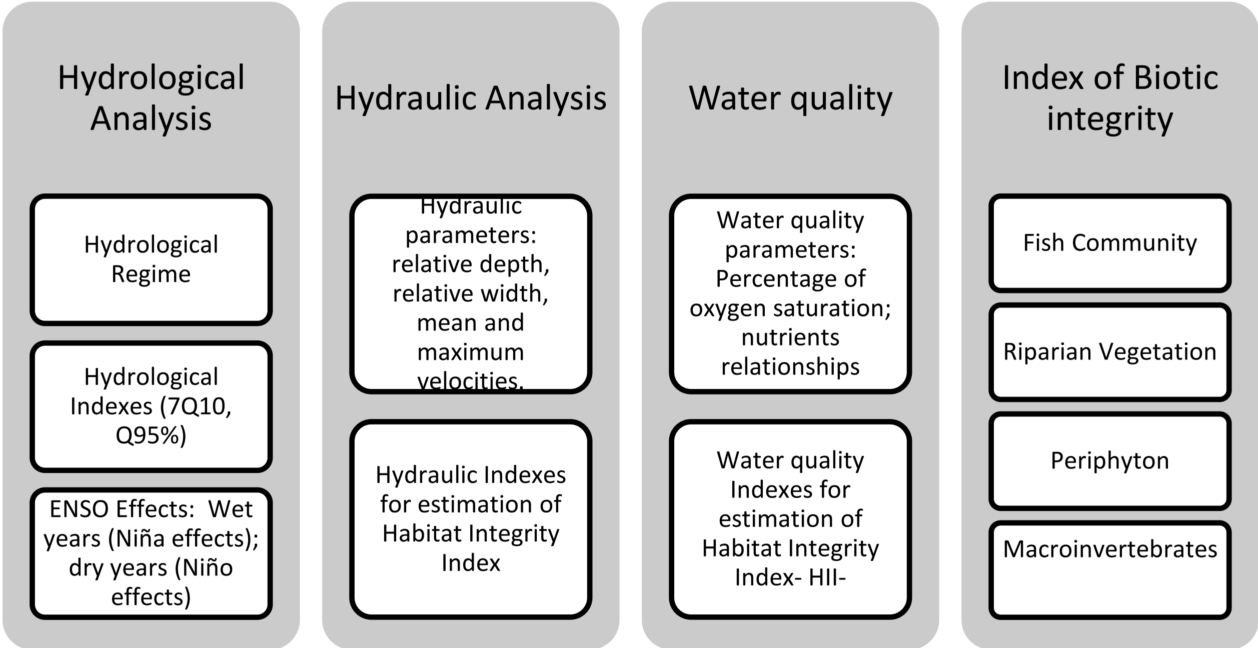


Figure 1. Conceptualization of methodologies for estimation of environmental flows in licensed projects in Colombia. Adapted from UN-MADVT (2008)

This basin exhibits water stress and high water vulnerability, because of the high demand of water for hydropower generation and the development of industrial, mining, livestock and agricultural activities. Moreover, water retention and regulation index is low so the river is susceptible to sudden increases and decreases in stream flow. Due to the geographical position, ENSO affects the hydrological regimen. (Ocampo and Vélez, 2014).

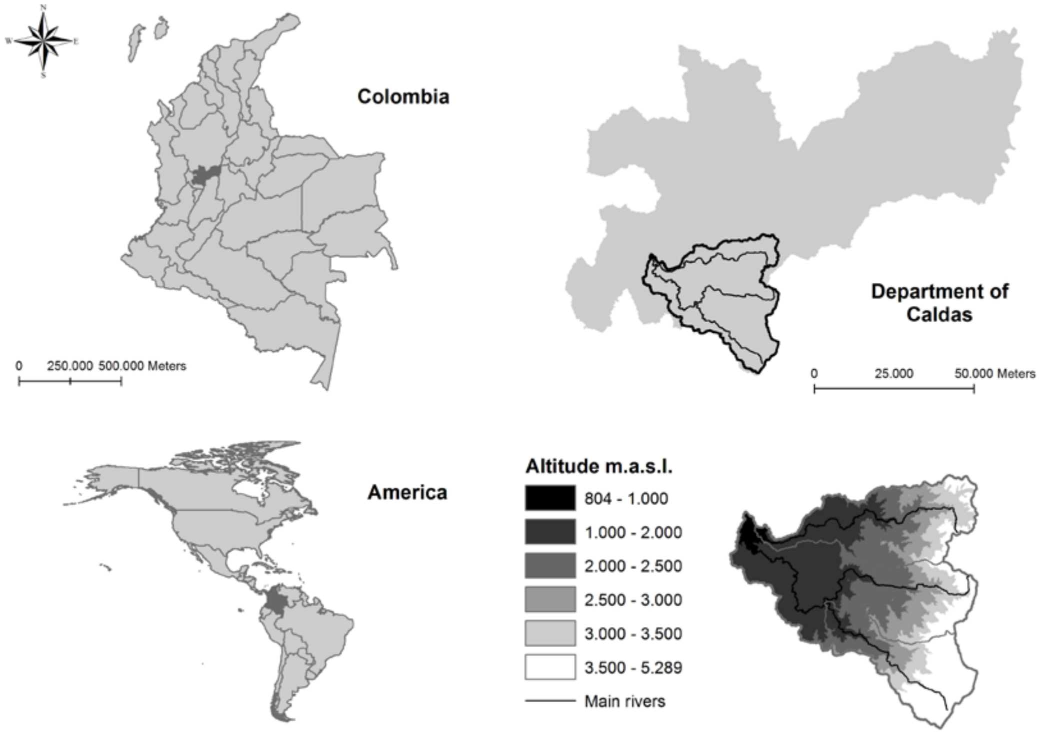


Figure 2. General location of Chinchiná River Basin and DEM

Because of its biodiversity and the ecosystem services, the Chinchina River Basin was selected by the Ministry of Environment as one of the pilot basins for defining integrated water management plans in Colombia. For the definition of these plans, the estimation of environmental flow is required. The importance of maintaining the ecological flows is related to the change of land use because habitats and ecosystems are being lost, but they must be conserved and preserved to ensure the ecosystem services.

The hydroclimatic analysis of variables was performed from available daily records of stations located in the basin for the period 1981-2010, according to supplied data by IDEAM, Hydroelectric CHEC, the National Coffee Centre Research -CENICAFE- and the National University of Colombia in Manizales. For this study, 25 rain gauge stations were selected and four (4) flow discharge gauge stations were used, where “El Retiro” discharge station is located at the mouth of the basin and “Chupaderos”, “Sancancio” and “Montevideo” are located in the middle part of the basin, all available stations are shown in Figure 3.

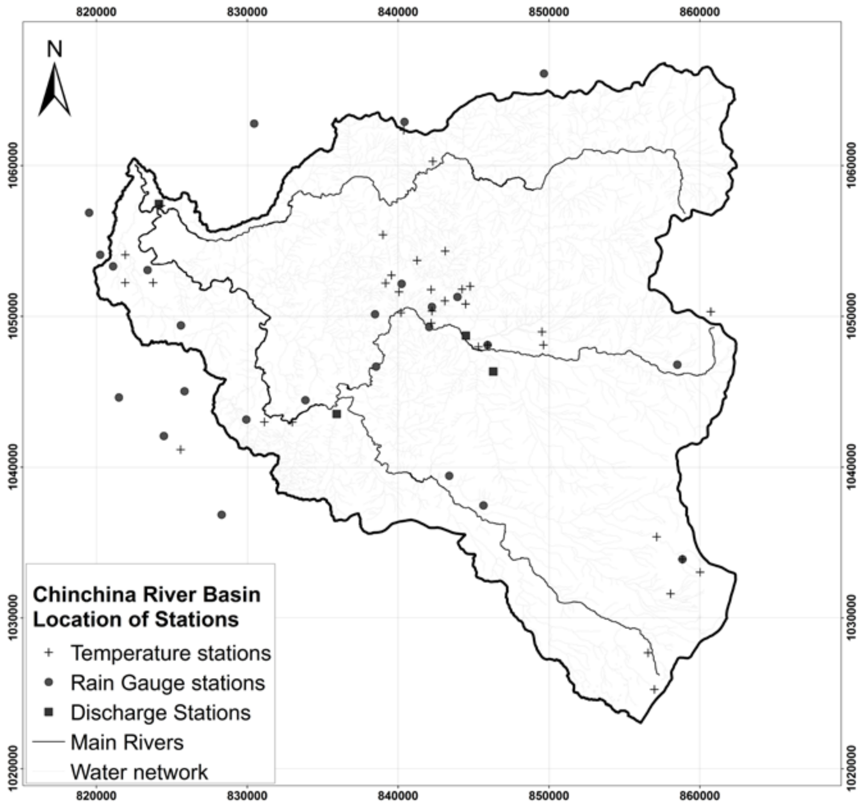


Figure 3. Location of stations in the Chinchina River Basin

In addition to the analysis of observed flow records, hydrological modeling was performed to determine the hydrological regime. The TETIS model was applied in this case study as a lumped model (Francés et al., 2007). The selected hydrological model is based on a tank model (conceptual model with physically based parameters). This model has been developed for simulating in natural hydrological basins and seeks the hydrological response caused by precipitation, taking into account the different involved physical processes. The vertical connections between tanks describe the processes of precipitation (rain), evapotranspiration, infiltration and percolation; the horizontal flow is represented by direct runoff, interflow and base flow. Finally, output to groundwater is considered in the lower tank to close the water balance (Frances et al., 2007).
During calibration and validation process, the performance of the model was estimated using both graphic and statistical analysis; in the latter case the recommended parameters were taken into account according to Moriasi et al (2007) who consider the Nash-Sutcliffe efficiency index -NSE-, the mean absolute error-MAE, the square root of the mean error -SRME-, the ratio of RMSE and standard deviation -RSR- and bias percentage -PBIAS-.
Furthermore, it was necessary to consider the impact of microclimate events detected during ENSO, based on the Oceanic El Niño Index -ONI-, so the flow rates were established according to: 1) the wet hydrologic condition -during La Niña years, 2) mean hydrological condition or normal years and 3) dry hydrological condition during El Niño years.
Hydrological, hydraulic and holistic methods proposed by the IDEAM (2008, 2010), the MADVT (2004), MADS (2013), UN-MADVT (2008) and INGETEC (2014) were evaluated in this comparative study to estimate the ecological and environmental flows as indicated in Table 2.

Table 2. Some methods for Estimating Ecological and Environmental Flows in Colombia

Reference	Flow Type	Methodology	Identification	Description
(IDEAM,	Ecological	Hydrologic	EFM-2000	Multiyear average flow

2000)	minimum			persists 97.5% of the time estimated from the FDC.
(IDEAM, 2004)	Ecological minimum	Hydrologic	EFM-2004-I	It corresponds to 25% of the lowest monthly average flow in the stream
(MAVDT, 2004)	Ecological minimum	Hydrologic	EFM-2004-M	It corresponds to 25% of the lowest monthly average flow in the stream. It can be considered an addition of 25% percentage by water quality effects.
(UN-MAVDT, 2008)	Environmental	Holistic	EFM-2008	The first approach considers the maximum value among the 7Q10% by Q95 and hydrologic condition. Environmental flows should be adjusted according to the criteria of integrity of the habitat.
(IDEAM, 2010)	Environmental	Hydrologic	EFM-2010	It is based on the rate of retention and hydrologic regulation index, HRI. If less than 0.7. IRH corresponds to 75% of the CDC; otherwise 85%.
(MADS, 2013)	Environmental	Holistic	EFM-2013	The first approach considers the maximum value between 7Q10, Q95 and Q75 for hydrological condition. Environmental flows should be adjusted according to the criteria of integrity habitat.
(INGETEC, 2014)	Ecological minimum	Hydrologic	EFM-2014	Based on flow duration curve, 15% excluding the 5% of extremes

Finally, an analysis of the uncertainty associated with the estimation of ecological and environmental flows is performed, considering various criteria according to the methodology used in the estimation (Redondo and Rodriguez, 2011; Ocampo and Velez, 2014): In hydrological methods, uncertainty is associated with the confidence interval (95%) and errors in modeling; which are considered for the RSU analysis parameters, that measures the relative standard uncertainty corresponding to the coefficient of variation expressed as a percentage (Herschy, 2002).

RESULTS AND DISCUSSION

The sectoral participation of potential water demand in Colombia, according to National Water Studies (IDEAM, 2010) is as follows: 1) Agriculture 54%; 2) Energy 19,4%; 3) Human consumption 7.3%; 4) Aquaculture 7.2%; 5) Livestock 6.2%; 6) Industrial 4.4%; 7) Services 1.5%. Most sectoral demand is the result of agricultural and livestock vocation of the country.

The Caldas Department is also characterized by its agriculture, mainly coffee, and cattle vocation; in consequence, without considering the demand for electricity generation, the sectoral distribution of the water demand is 71% for domestic use, 19% industrial, 3% and 7% livestock services (IDEAM, 2008). The environmental authority on behalf of the Regional Autonomous Corporation of Caldas- CORPOCALDAS reports its environmental management plan for the department (PGAR 2007-2019) that the water demand is increasing in relation to water supply.
According to the diagnostic report of the comprehensive water resources plan in the Chinchina River Basin, the sectoral water demand is as shown in Table 3 and the participation is summarized in Figure 4. The high water demand for electricity production in this basin is evident.

Table 3. Sectoral Water Demand in Chinchina River Basin

Sector	**Water Demand (Mm^3)**
Energy	571,39
Human consumption	55,94
Livestock	18,82
Industrial	10,03
Services	4,15
Aquaculture	0,37
Agriculture	2,39
Total	**663,09**

Data Source: (UNAL- CORPOCALDAS, 2014)

The water extraction in Chinchiná River Basin for different uses, especially for hydropower generation, have been modifying the stream flow profile as shown in Figure 5. These measurements have been made by different stations (E) located in the path of the river. Consequently, five sections are identified, where the stream flow profile changes with consequences on the water quality (UNAL-CORPOCALDAS, 2014) as shown in Figure 5.
The water quality of the river Chinchiná has been evaluated along the different station located in the river. The map in Figure 6 summarizes the results expressed in terms of water quality index, which was calculated with the methodology proposed by the IDEAM (2010). However, the classical methodology ICA (CETESB, 2006) suggested that the water quality indexes are bad in most of the river path as shown in Figure 7.

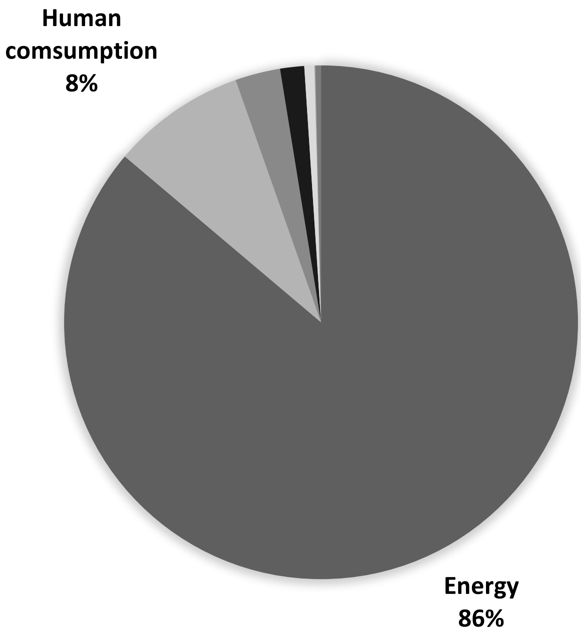


Figure 4. Percentage of water demand of each sector
Data Source: (UNAL- CORPOCALDAS, 2014)

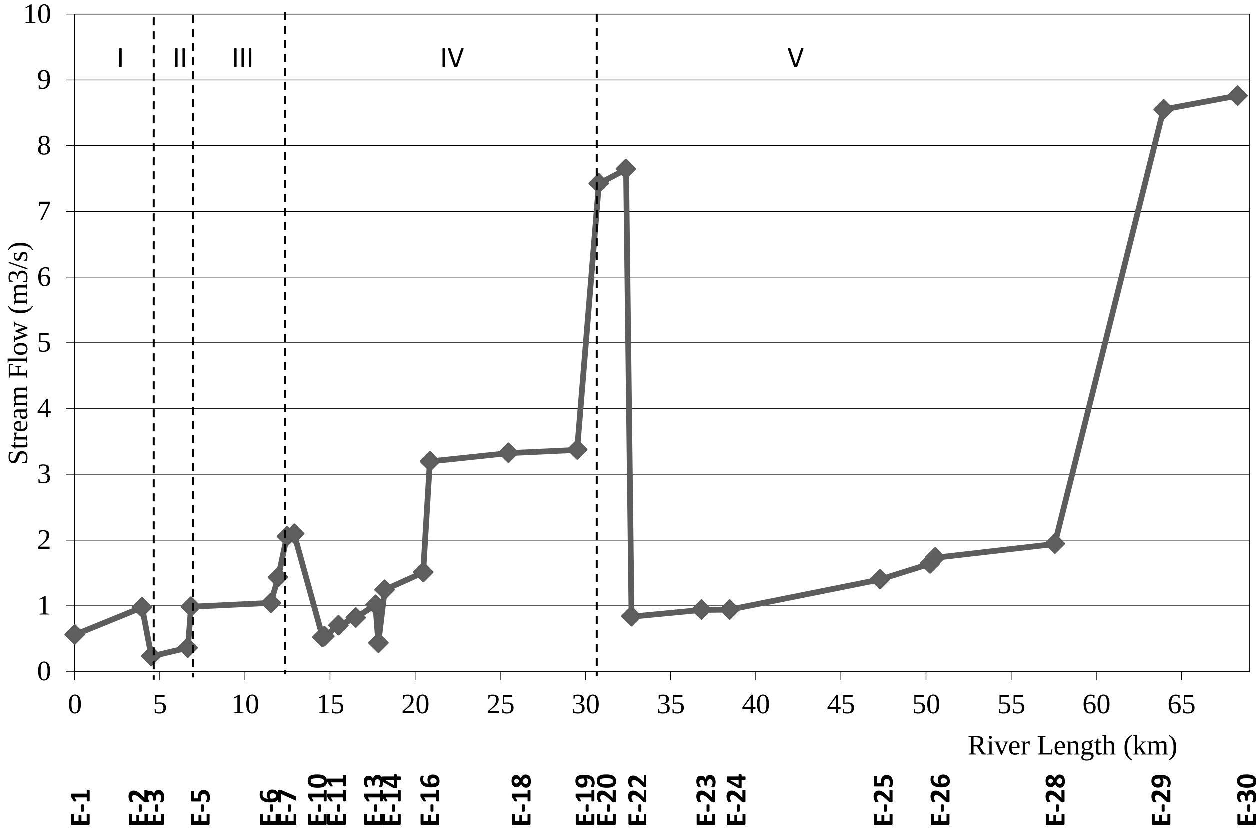


Figure 5. Stream Flow profile Chinchina River Basin
Data Source: (UNAL- CORPOCALDAS, 2014)

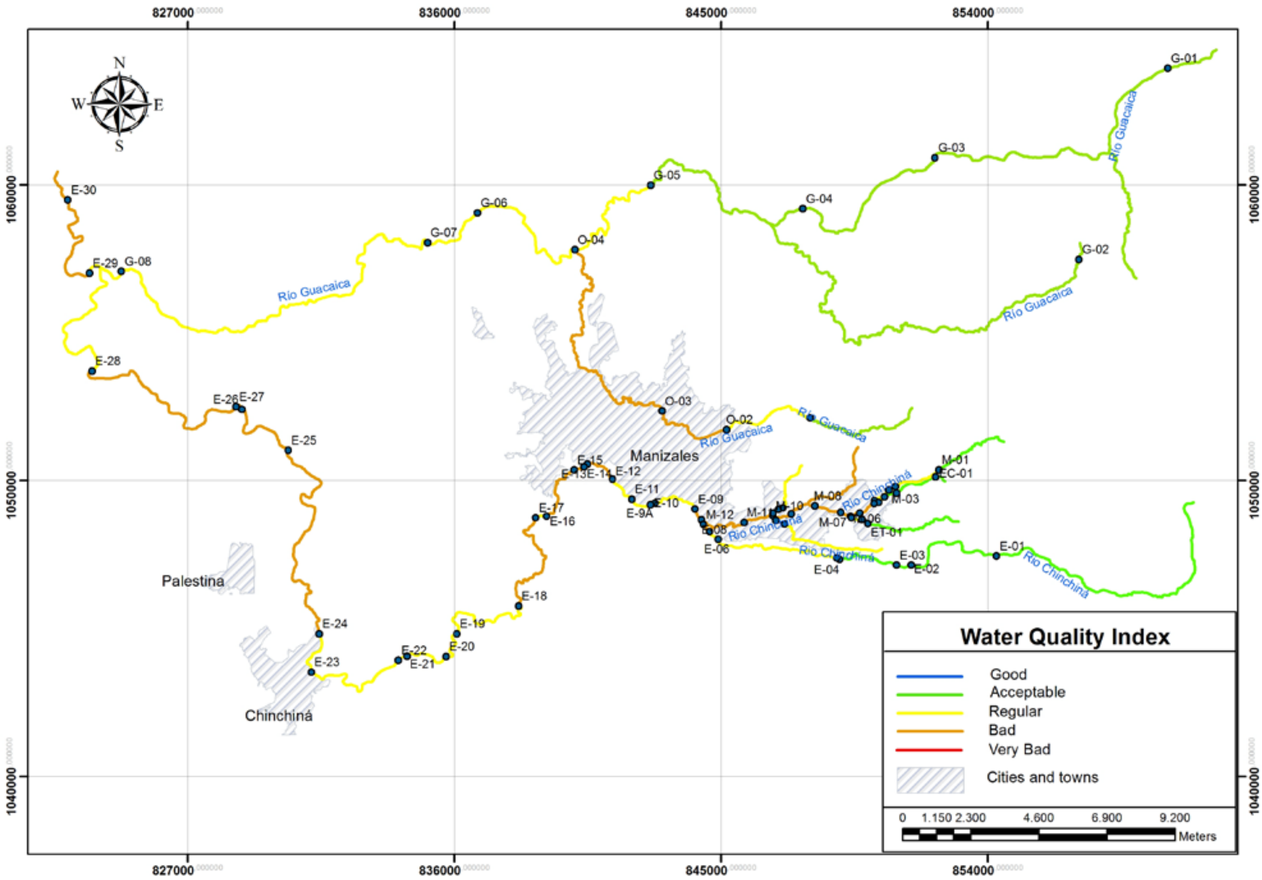


Figure 6. Water quality Index ICA-IDEAM Chinchina River Basin
Data Source: (UNAL- CORPOCALDAS, 2014)

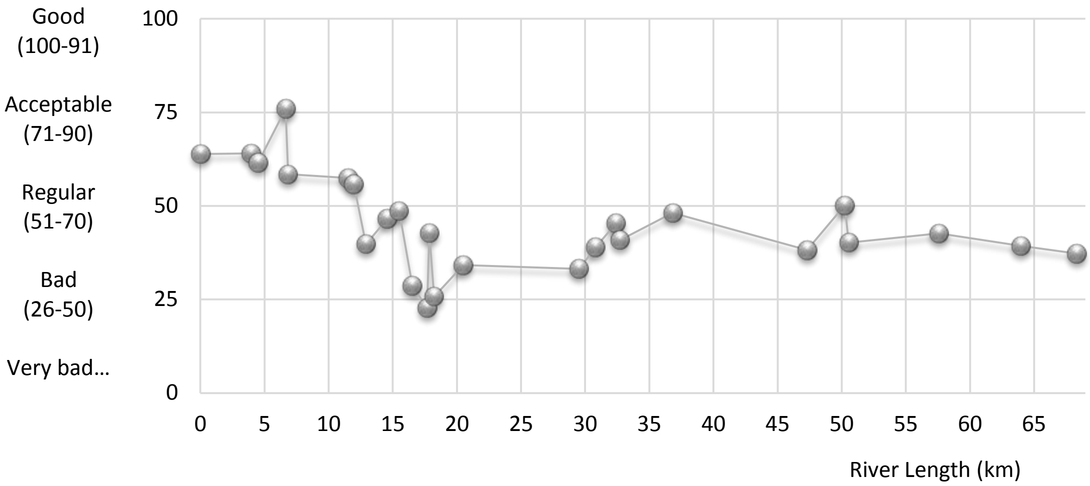


Figure 7. Water quality Index ICA-CETESB Chinchina River Basin
Data Source: (Ocampo, Vélez and Londoño, 2014)

These problems in water quality affect the index of biotic integrity. The biomarkers are used to estimate this index. These biomarkers are an effective tool to meet water quality from the biological point of view and complements the traditional method of physicochemical analysis. As biological quality indicators have different taxa that reveal the status of the water. The methodology proposed by IDEAM-UNAL (2008) recommended the following biomarkers:

1) **Periphyton** refers to communities of algae in rivers that are attached to the sediment surface or rocks; 2) **Riparian vegetation** is compound by plant communities adjacent to the banks of rivers, includes vegetation found neighboring rivers and streams; 3) **aquatic macroinvertebrates** are those invertebrates than can be captured by a 500 μm net or sieve and include arthropods, molluscs, annelids, nematodes and Platyhelminthes; 4) **fishes** are those vertebrates which are indicators for susceptibility to hydrological and physicochemical changes. The Table 4 summarized the indexes of biotic integrity for these biological communities.

Where indexes of biotic integrity are lower than 0.3, the biotic integrity is low and the ecological status is poor for communities. If the index varies from .31 to 0.60, the integrity biotic is moderated. Therefore, low indexes of biotic integrity were found at stations located in Chinchina River Basin with the exception of San Julian where the index of biotic integrity was moderated.

Table 4. Indexes of biotic Integrity in different stations of Chinchina River

Community	RioClaro River Station	Saint Julian Station	Montevideo Station	Sancancio Station	Cenicafé Station
Periphyton	0,18	0,11	0,14	0,14	0,14
Riparian Vegetation	0,40	0,43	0,43	0,38	0,28
Macroinvertebrates	0,52	0,44	0,32	0,52	0,24
Fishes	0,00	0,52	0,2	0,00	0,00
Global index	0,28	0,38	0,27	0,26	0,17

Data Source: (UNAL- CORPOCALDAS, 2014)

The amount of water in the basin was determined by hydrological modeling using the model TETIS. The hydrographs obtained during calibration and validation of the TETIS model (Ocampo et al. 2013) allowed for the estimation of the maximum and minimum flows that can be seen in Figure 8. These results confirm the satisfactory fit of the model capturing seasonality. The percentage bias or PBIAS was only 1.4% considering the average flow rates of 4.5% and the average flows estimated by the 50th percentile.

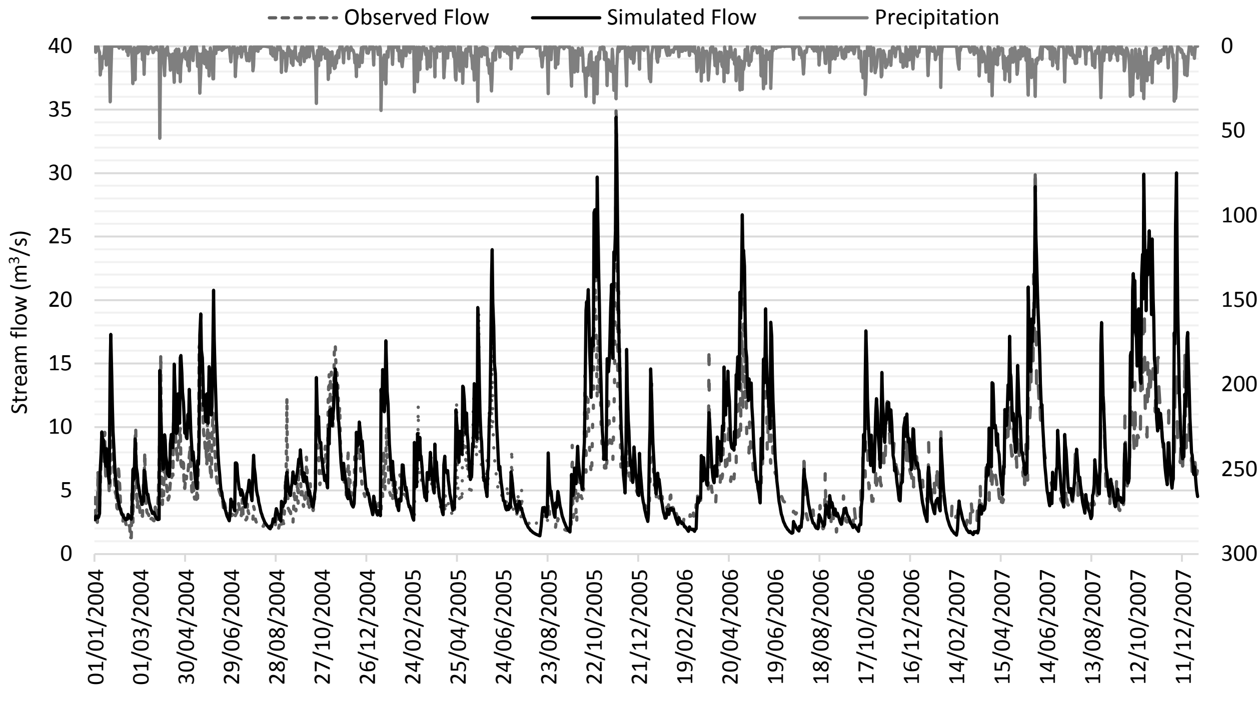


Figure 8. Observed and simulated discharges using TETIS model during the validation process, (2004-2007) at Sancancio gauge station.

The hydrologic modeling allowed the estimation of the hydrological regime for the period 1981-2010 which is illustrated in Figure 9, where a typical bimodal seasonal behavior can be observed. This behavior is typical of Colombian Andean due to the displacement of the Intertropical Confluence Zone - ZCIT-. Figure 5 also shows the confidence interval for the average flow of the basin (α = 95%).

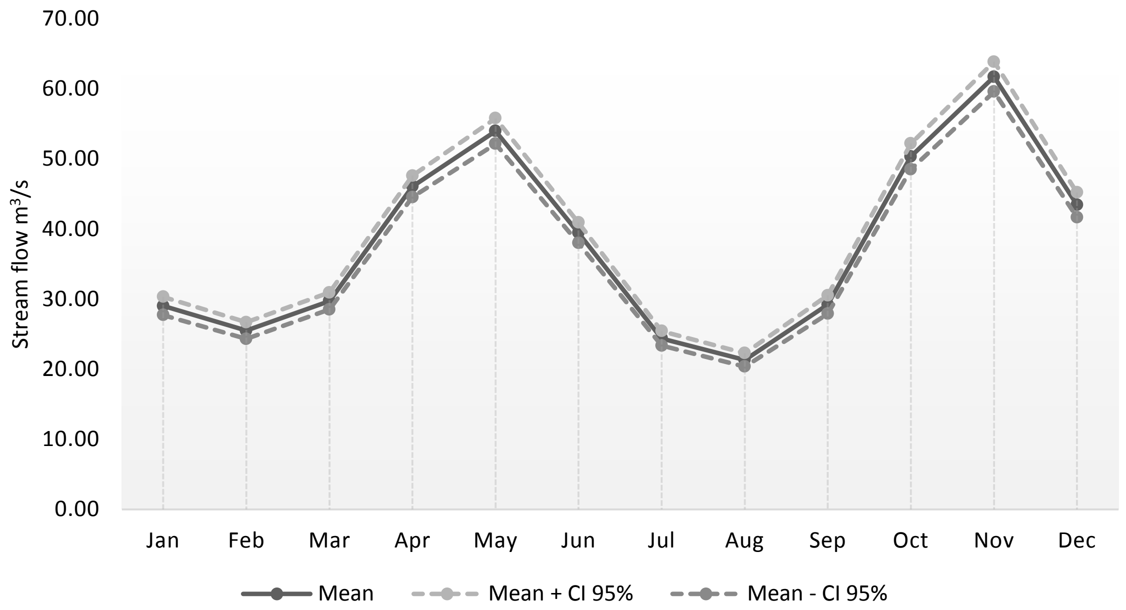


Figure 9. Hydrological regime in Chinchiná River Basin (1981-2010) estimated by TETIS Model

In order to analyze the effects of climate variability on water supply, average flow rates were evaluated considering the classification of data into categories according to the value of the Oceanic El Niño Index, ONI, which identifies normal periods as those without the ENSO presence; wet years characterized by La Niña event and dry years with the presence of El Niño. The results of hydrological condition are summarized in Figure 10. During La Niña events increased flows especially in the second half of the year is evident; while El Niño events are having a reduced flow rates, mostly during the first quarter of the year. The increase in flow is 27% for La Niña events while a reduction about 25% is estimated during El Niño events.

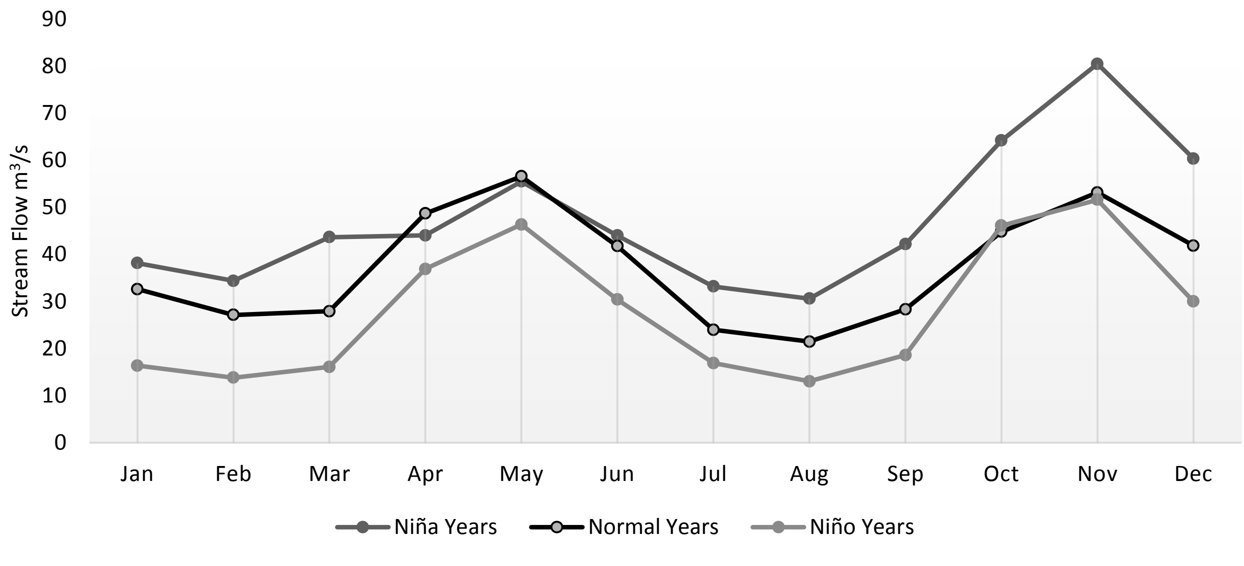


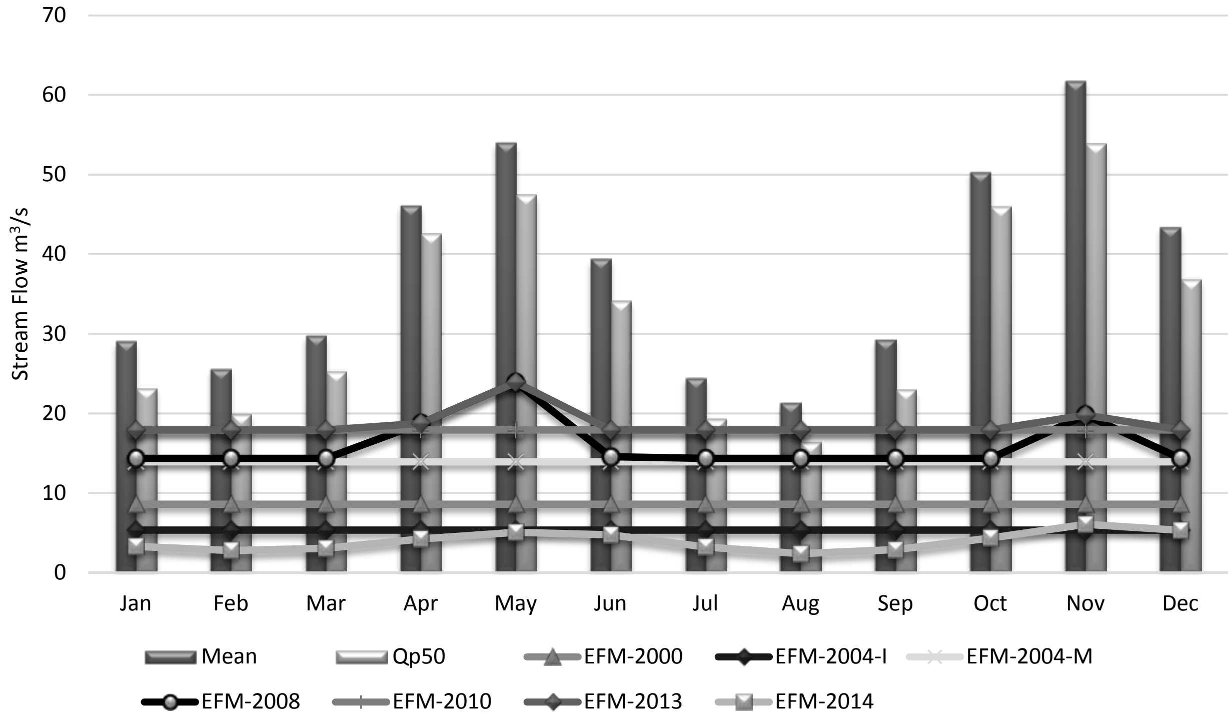
Figure 10. Monthly variability during the hydrological regime ENSO in Chinchina River Basin (1981-2010)

The environmental and ecological flows at the Chinchiná river basin were estimated using different methodologies –EFM, as shown in Table 2. The mean values are summarized in Table 5 and Figure 11 shows the results at the El Retiro gauge station. According to the variance analysis, there are statistically significant variations between different methodologies proposed by the Colombian regulations during the determination of ecological and environmental flows in the Andean basins.

Table 5. Ecological and Environmental flows in the Chinchina River Basin

Method			Flow type	Environmental flow, m^3/s	RSU %
No	Identification	Reference			
1	EFM-2000	(IDEAM, 2000)	Ecological minimum	8.58	34.6
2	EFM-2004-I	(IDEAM, 2004)	Ecological minimum	5.33	11.0
3	EFM-2004-M	(MAVDT, 2004)	Ecological minimum	13.91	26.7
4	EFM-2008	(UN-MAVDT, 2008)	Environmental	15.97	18.1
5	EFM-2010	(IDEAM, 2010)	Environmental	17.91	14.7
6	EFM-2013	(MADS, 2013)	Environmental	18.63	13.6
7	EFM-2014	(INGETEC, 2014)	Ecological minimum	3.95	66.8

These methodologies in charge of estimating a single value for the whole year, as the methods 1, 2, 3 and 5, can only be considered as a first approach to minimum ecological or environmental flows. Methodologies 4 and 6 are more appropriate because they consider the effect on hydrological regime under the influence of ENSO that affects the seasonal flow regime in the Colombian Andean basins. The last methodology underestimates the ecological flow, but it can be raised up if biotic and habitat restrictions are included.



Each estimation methodology has an uncertainty which was calculated by statistical procedures whose results are presented in Table 5. The lowest relative uncertainty -RSU- was obtained with methods 2 (IDEAM, 2004) and 5 (IDEAM, 2010) based on hydrological criteria. The holistic methods 4 (UN-MAVDT, 2008) and 6 (MADS, 2013) also showed low uncertainties. Higher uncertainties are obtained with the holistic method 7 (INGETEC, 2014).
Methods that consider the natural variability of the streamflow and have less uncertainty such as 4 (UN-MAVDT, 2008) and 6 (MADS, 2013) are valid for estimation of the environmental flow in different water regimes. The estimation of environmental flows including hydrological condition with the method 4 (UN-MAVDT; 2008), is presented in Figure 12

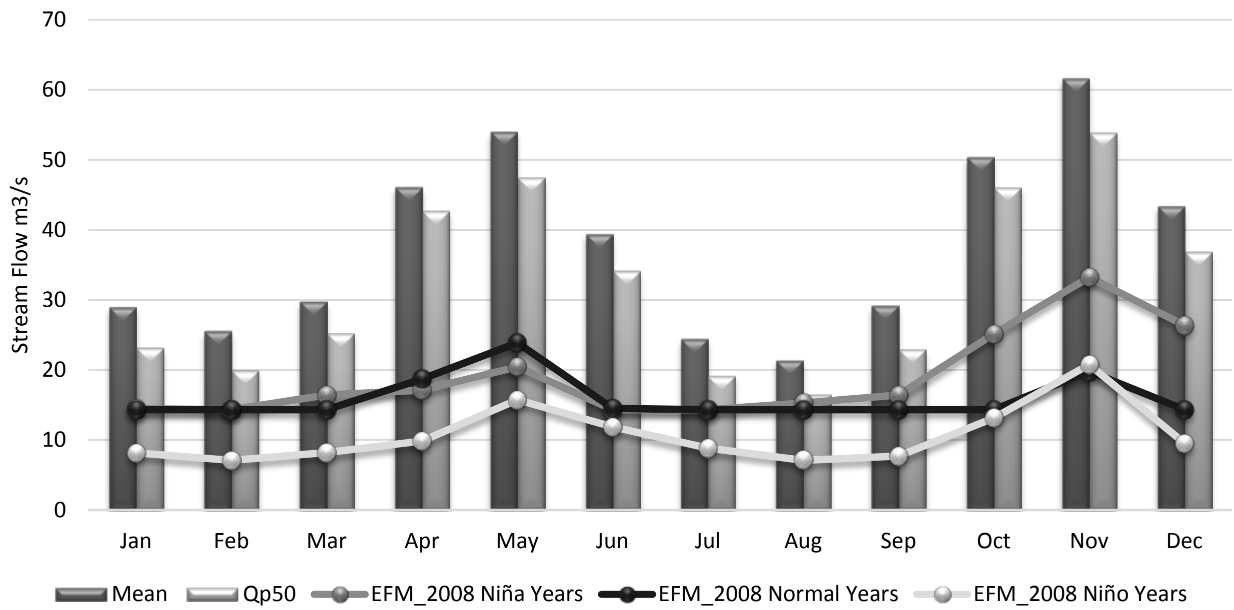


Figure 8. Environmental flows in the Chinchina River Basin for different hydrological conditions at El Retiro gauge station.

It is important to highlight that those methods are able to estimate environmental flow in different hydrological regimes such as dry hydrological conditions due to El Niño and humid conditions during La Niña, because these macroclimatic events affect the seasonality and inter-annual variability in the basin and should be included in the analysis performed by decision makers.

CONCLUSIONS

This article compares and discusses different methodologies for the estimation of the environmental and ecological flows applied in an Andean basin in Colombia. Some of these methodologies estimate a single value for the whole year, therefore they can only be considered as a first approximation of the ecological minimum flow. It is necessary to consider hydrological, hydraulic and habitat criteria in the estimation of environmental flow in Andean watersheds, because the temporal variability of flows along the year affects the results, this variability is due to macroclimatic phenomena such as ENSO and ITCZ. This study concludes that methods considering hydroclimatological variability and the influence of macroclimatic phenomena are most appropriate for Colombian Andean basins and should be considered during Water Resources Management studies. The discussion is still open and different environmental agencies in Colombia are currently proposing some modifications to all of these methodologies in order to implement a new guide of estimation of environmental flows in Colombia.

The authors are pretty concern because public health topics are not included in the determination of minimum environmental flows in Colombia, so this must be included in future proposals for the environmental flow estimation.

REFERENCES

Boodoo, K., McClain, M., Velez, J and Ocampo, O. (2014). Impacts of implementation of Colombian environmental flow methodologies on the flow regime and hydropower production of the Chinchiná River, Colombia. Ecohydrology and Biohydrology.

Brown, C. A. and King, J. M. (1999). Consulting services for the establishment and monitoring of the instream flow requirements for river courses downstream of the Lesotho Highland Water Project dams. Lesotho Highlands Development Authority, Lesotho.

Caissie, D. and El-Jabi, N. (1995). Comparison and regionalization of hydrologically based instream flow techniques in Atlantic Canada. *Can J. Eng.* Vol 22.235-246.

Castro L. M., Carvajal Y. and Monsalve E. A. (2006). "Enfoques teóricos para definir el caudal ambiental". Ingeniería y Universidad. Vol 10, Num 2. Pontificia Universidad Javeriana Colombia.

Francés F., Vélez J. I and Vélez J. J. (2007). "Split parameter structure for the automatic calibration of distributed hydrological models". Journal of Hydrology, 332, p 226-240.

Gordon, N. D., McMahon, T. A. and Finlayson, B. L. (1992). Stream Hydrology. An Introduction for Ecologists. John Wiley & Sons: Chichester.

Gore, J. A., Nestler, J. M. (1988). "Instream flow studies in perspective". Regulated Rivers: Research and Management 2: 93–101.

Herschy, R.W. (2002). "The uncertainty in a current meter measurement" Flow measurement and instrumentation, 2002: 13: 281-284.

IDEAM. Instituto de Hidrología, Meteorología y de Estudios Ambientales de Colombia (2000). Estudio Nacional del Agua. Bogotá.

IDEAM. Instituto de Hidrología, Meteorología y de Estudios Ambientales de Colombia (2004). Estudio Nacional del Agua. Bogotá.

IDEAM. Instituto de Hidrología, Meteorología y de Estudios Ambientales de Colombia (2008). Estudio Nacional del Agua. Bogotá.

IDEAM. Instituto de Hidrología, Meteorología y de Estudios Ambientales de Colombia (2010). Estudio Nacional del Agua. Bogotá.

King J. M., Tharme R. E. and Villiers M. S. (2008). Environmental Flow Assessments for Rivers: Manual for the Building Block Methodology. 339 p.

MADS. Ministerio de Ambiente y Desarrollo Sostenible. (2013). Metodología para la estimación y evaluación del caudal ambiental en proyectos que requieren licencia ambiental. Bogotá.

MAVDT. Ministerio de Ambiente, Vivienda y Desarrollo Territorial. (2004). Resolución 865 de 2004. Bogotá, Colombia

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D. and Veith, T.L.(2007). "Model evaluation guidelines for systematic quantification of accuracy in watershed simulations", Transactions of the ASABE 50 (3), 885-900.

Nestler J. M., Milhous R. T., Layzer J. B. (1989). "Instream habitat modeling techniques". In Alternatives in Regulated River Management, Gore JA, Petts GE (eds). CRC Press: Florida; 295–315.

Ocampo, O. y Vélez J.J. (2014). "Environmental flow analysis in an Andean Basin applying hydrological and hydraulic criteria". International perspective on water resources & the environment. Quito, Ecuador.

Ocampo, O., Vélez J.J. y Londoño A. (2012). "Vulnerabilidad al cambio climático y a la variabilidad climática en cuencas hidrográficas de alta montaña; río Chinchiná, Colombia". XXV Congreso Latinoamericano de hidráulica. San José, Costa Rica

Ocampo, O., Vélez J.J. y Londoño A. (2014). "Análisis de vulnerabilidad hídrica en la cuenca del río Chinchiná". Universidad Nacional de Colombia sede Manizales. Facultad de Ingeniería y Arquitectura. Manizales, 220 pag.

Poff, N. L., Richter, B. D., Arthington, A. H., Bunn, S. E., Naiman, R. J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B. P., Freeman, M.C., Henriksen, J., Jacobson, R. B, Kennen, J. G., Merritt, D. M., O'Keeffe, J. H., Olden, J. D., Rogers, K., Tharme, R. E. and Warner, A. (2009). "The Ecological Limits of Hydrologic Alteration (ELOHA): A New Framework for Developing Regional Environmental Flow Standards". Freshwater Biology 55:147-170.

Redondo, S. A. and Rodriguez, E. A. (2011). Incertidumbre hidrológica en la estimación de caudales ambientales mediante metodologías basadas en series históricas. Universidad Nacional de Colombia, Bogotá, Colombia.

Reiser, D. W, Wesche, T. A. and Estes, C. (1989). “Status of instream flow legislation and practise in North America”. Fisheries 14(2): 22–29.

Richter, B. D., Baumgartner, J. V., Powell, J. and Braun, D. P. (1996). “A method for assessing hydrological alteration within ecosystems”. Conservation Biology 10(4): 1163–1174

Swales, S., Bishop, K. A., Harris, J. H. (1994). “Assessment of environmental flows for native fish in the Murray-Darling Basin—a comparison of methods”. In Proceedings of Environmental Flows Seminar. Australian Water and Wastewater Association Inc.: Artarmon, NSW, Australia; 184–192.

Tennant, D. L. (1976). “Instream flow regimens for fish, wildlife, recreation and related environmental resources”. Fisheries 1(4): 6–10.

Tharme, R. E. (1996). Review of international methodologies for the quantification of the instream flow requirements of rivers. Water law review. Final report for policy development. Commissioned by the Department of Water Affairs and Forestry, Pretoria. Freshwater Research Unit, University of Cape Town, Cape Town. 116 pp.

Tharme, R. E. (2003). “A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers”. River Research and Applications, 19, 397–441

UN-MAVDT. Universidad Nacional de Colombia y Ministerio de Medio Ambiente, Vivienda y Desarrollo Territorial. (2008). Metodología para la estimación del caudal ambiental en proyectos licenciados. Bogotá. 135 p.

USFWS, (1981). Interim regional policy for New England stream flow recommendations. Memorandum from H.N. Larsen Director, Region 5 of U.S. Fish and Wildlife Service, Newton Corner, Mass.