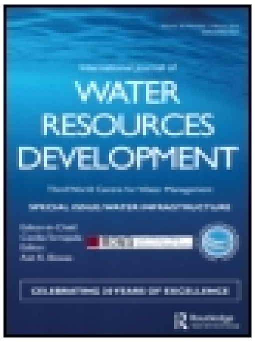

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Modelling water stress vulnerability in small Andean basins: case study of Campoalegre River basin, Colombia

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ABSTRACT

The Campoalegre River basin and its sub-basins present water-use conflicts. This study seeks to analyze these conflicts using a disaggregated quantitative approach, so as to better understand existing and potential water stress. We find that the estimated future flows are not sufficient to meet future demand, which will create significant water stress, particularly in certain sub-basins. A tool is provided for decision makers to identify potential future water conflicts, as well as strategies to reduce system vulnerability. This study is relevant for other watersheds where pressure on water resources may intensify due to increased water demands.

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Andean basins; vulnerability; hydrological modelling; WEAP; integrated water modelling; water conflict; small basins

Introduction

Water resource planning is critical for the determination of aspects that may affect a region's future water supply and is an important component for the development of communities and human activities. It has become an even more critical issue in recent decades, due to increasing pressure on water basins, uncertainties generated by climate change, and rapid variation in socio-economic conditions. More attention must be devoted to understanding water resources and management of the transition to more adaptive water management approaches. This implies a water management paradigm shift, from a prediction-and-control approach to a learning approach (Pahl-Wostl, 2007).

Even in countries that are rich in water resources, regional shortages may occur due to differences in the spatial and temporal distribution of water. Water shortages may be intensified by factors including population distribution, water body contamination, and rising water demand. Latin America is facing a growing challenge in water management, as well as conflicts caused by competition for water resources or by extreme events (Guzmán-Arias & Calvo-Alvarado, 2013).

Colombia, in particular, is rich in water resources, compared to other countries worldwide (FAO, 2003). According to the Institute of Hydrology, Meteorology, and Environmental Studies (Instituto de Hidrología, Meteorología y Estudios Ambientales [IDEAM]), Colombia has a median annual runoff of 1830 mm (61% of annual rainfall). Surface runoff is distributed

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into five major hydrological regions nationally. However, only 11% goes to the Magdalena-Cauca region (Ministerio de Ambiente y Desarrollo Sostenible de Colombia, 2010), where 80% of the Colombian population lives. This puts intense pressure on water bodies, and in some cases causes water stress (Corporacion Autonoma Regional del Rio Grande de la Magdalena and IDEAM, 2001), understanding 'pressure on water resources' as increasing demand for water, and 'water stress' as when water demand outweighs water supply for some period of time. Pressure on water resources may harm the environment and undermine socio-economic development (MADS, 2010).

In the Colombian coffee-growing region, water balance and climate change assessments have been carried out in the past five years, especially in the Chinchiná and Otún River basins (Claure Pereira, Portocarrero Lau, & Valencia Quintero, 2015; Purkey & Escobar, 2015). These studies have sought to characterize the conditions of these basins and the impact of climate change there and to develop tools to support decision makers. These studies have helped characterize the high variability of climatic conditions in this Andean region, as well as the impacts of this variability on local supply–demand conditions. They have also served as an example of the kinds of analyses necessary to tackle complex regional water management challenges.

The Campoalegre River basin is contiguous with the Chinchiná and Otún watersheds and has similar climatic and water-demand challenges. The variety of uses of water and the way some of the Campoalegre's water is diverted to different watersheds adds complexity to water management in this area. In the basin, for example, the return flows from significant hydropower water use are discharged into neighbouring basins, and so act as water transfers. These transfers, along with human, agricultural, livestock, industrial, aquaculture and recreational water use, have drastically and permanently reduced the supply of water downstream. Some water transfers go to the two adjacent river basins, the Chinchiná to the north and the Otún to the south. These two basins belong to separate hydrographical planning units, managed by separate water management authorities. This governance system, in which water transfers may not be accounted for within planning units, exacerbates the challenges of implementing water management strategies and policies. These challenges are beyond the government's sole capacity to address, and so have required the support of both civil society and academia (OECD, 2015).

Water balance (supply and demand) studies are generally carried out in an aggregated form in basins, where water demand is accumulated and streamflow at the mouth of the basin is considered. In these cases, pressure on the water resources or conflicts over water uses may not be identified. In this study, we disaggregated supply and demand, by basin, in a monthly representation. The local actors who participated in this study are aware of the critical situation and believed that this study could help them identify ways to reduce the vulnerability of the basin.

The goal of the study is to develop a water balance for the Campoalegre basin, to quantify the supply of and demand for water, understand the effects of these interconnected water-governance challenges, and evaluate the vulnerability of water-demand coverage. For the vulnerability evaluation, this study compared supply to demand to identify potential water surpluses (more supply than demand) and deficits (less supply than demand). In the face of deficits, the Autonomous Regional Corporations, the environmental authority in each Colombian department, are responsible for exploring options that might increase supply or reduce demand to achieve a secure water supply. To this end, the specific objectives of the present study were to assess the baseline conditions in the watershed, in terms of water demand and supply, in recent decades (1989–2015); to develop projections for how conditions related to water use and demand may change in the future (2018–2049); and to identify ways to reduce water vulnerability.

This study is innovative because the analysis of results serves local needs and was developed to be a decision-making tool for regional environmental authorities, which, until now, had no such resource. The article will be of interest to policy makers and water resource managers, as it helps identify current and potential future conflicts over water use and the possible need for rationing to reduce water stress.

Materials and methods

Study area

The Campoalegre River basin is part of a hydrographic management unit that includes neighbouring basins and forms part of the Cauca River basin. This unit has an approximate area of 640 km^2 and is on the western slope of the Central Andes mountain range, in the 'coffee region' of the Caldas and Risaralda Departments. It encompasses the municipalities of Palestina, Villamaría and Chinchiná in the department of Caldas (21.5% of the total area), and the municipalities of Dosquebradas, Pereira, Marsella and Santa Rosa de Cabal in the department of Risaralda (78.5% of the total area) (Figure 1). The water bodies in the Campoalegre basin are of great importance in the region, as they feed both municipal and rural aqueducts. The Campoalegre, San Francisco and La Nona basins are also the main sources for the three principal hydroelectric power plants in the region.

Precipitation in the catchments in the study area is bimodal, with two wet seasons (March to May and October to November) and two dry seasons (June to August and December to February). This is typical in the Andean region, owing to the Intertropical Confluence Zone (ITCZ) (Poveda, 2004). The El Niño Southern Oscillation (ENSO) also affects the study area. Both ENSO and ITCZ, which are principal climate variability factors, increase vulnerability in the area, due to lack of knowledge and failure to integrate their impacts into planning efforts (Bedoya Soto, Poveda, Trenberth, & Vélez Upegui, 2019).

Multi-year average monthly evapotranspiration does not vary significantly and falls between 48 mm and 56 mm. Multi-year average monthly effective precipitation is 56 mm to 157 mm (typically lowest in August, and highest in November). The multi-year average monthly temperature is between 17.5 and 18.3 °C.

Methodology

The Water Evaluation And Planning system (WEAP, Version 2016.01), developed by the Stockholm Environment Institute, was used to develop the model to quantify the balance between water supply and demand. The program performs hydrological modelling and integrates water demands, considering location and priorities of use. WEAP employs a menu of different elements and procedures, which are accessible through an intuitive geographic information system–based graphical interface. This watershed representation may be used to analyze a wide range of concerns and uncertainties faced by water resource planners, including those related to climate, basin conditions, demand projections, regulatory conditions,

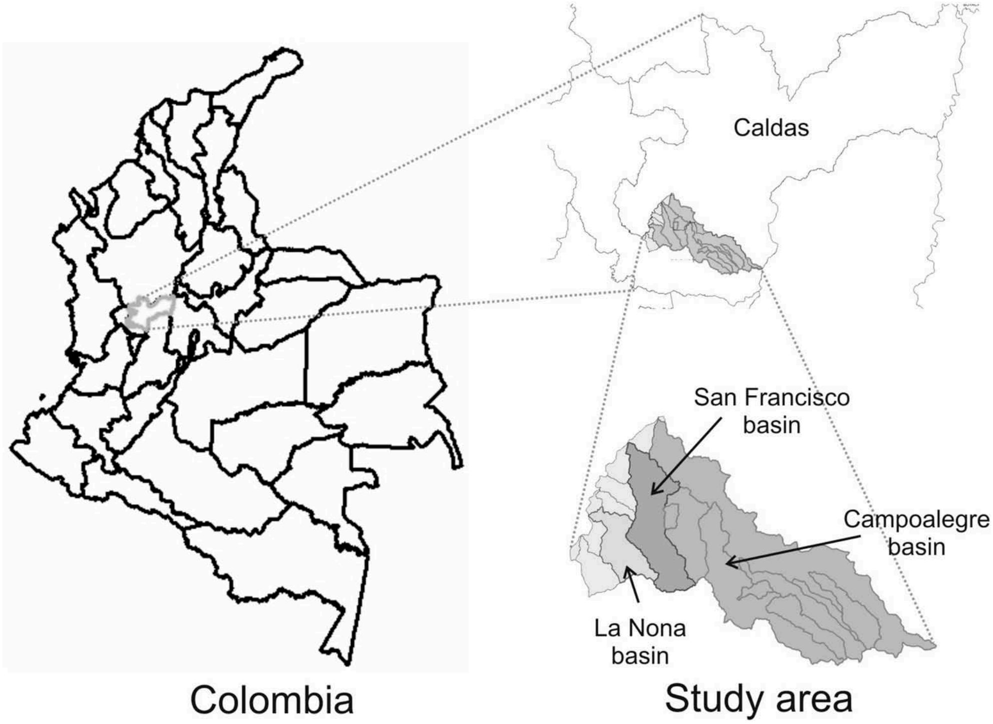

Figure 1. General location of the study area and protected areas within it.

operational objectives and available infrastructure. WEAP is distinguished by its integrated approach to simulating both the natural (agricultural demand, runoff, baseflow) and engineered (reservoirs, groundwater pumping) components of water systems (Stockholm Environment Institute, 2018). The software has been used in much research (Babel & Jensen, 2010; Droogers & Bouma, 2014; Goes, Howarth, Wardlaw, Hancock, & Parajuli, 2016; Polpanich, Lyon, Krittasudthacheewa, Bush, & Kemp-Benedict, 2017). It has been described in numerous publications (Purkey et al., 2007; Yates et al., 2009; Yates, Sieber, Purkey, & Huber-Lee, 2005), and a detailed description is available at www.weap21.org.

Figure 2 shows the stages implemented in the present study to develop the integrated water supply and demand model in WEAP.

Data used

The model employed hydro-climatological information, including daily time series for air temperature (13 stations) and precipitation (37 stations), multi-year monthly averages for relative humidity (445 stations in the entire country), wind (28 stations) and cloudiness fraction (336 stations in the entire country), and monthly streamflow averages (5 stations). This information was compiled from the stations of IDEAM and the stations of Caldas Hydroelectric Power Plants (Central Hidroeléctrica de Caldas [CHEC]), a regional power company. The time series were homogeneous, consistent and trendless (Wilson, 2016).

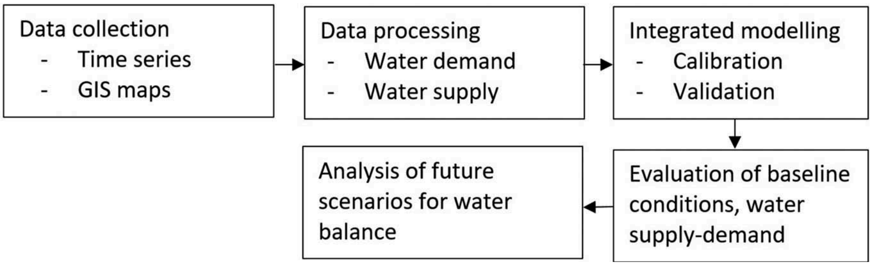

Figure 2. Broad steps of the model implementation.

To determine water demand and construct the model, several geographical information system layers were required, including a digital elevation model (NASA, 2013) and maps of land cover and use, hydrographic zoning, and soils (CARDER, 2011; CORPOCALDAS, 2011). Information was also collected on water intake, demand, and discharge locations. Within the study area, land cover was classified into forest (27%), permanent crops (24%), heterogeneous agricultural areas (17%), pasture (16%), scrub and/or herbaceous vegetation (13%), artificial surfaces (2%), inland water (0.7%), and open spaces with little or no vegetation (0.3%) (Figure 3).

Finally, data were gathered to characterize in detail each type of water demand and infrastructure. These data included annual activity levels, annual water use rates, monthly variations, losses, consumption, maximum flows diverted and environmental flows. Reservoir data included flood-control zones, conservation zones, buffer zones and inactive zones, as well as buffer coefficients, storage capacities, volume–elevation curves and maximum reservoir outflows. Data obtained from CHEC for hydropower plants (HPPs) included maximum turbine flow, tailwater elevation, plant factors, generating efficiency and hydropower priorities. All collected data were processed, verified, analyzed and validated to reduce uncertainties in the water balance model, using various techniques, including homogeneity and consistency analysis (Wilson, 2016).

Data processing

Water supply

The water supply was determined using the WEAP hydrology module, which estimates surface runoff, interflow and baseflow values by the soil moisture method (Sieber & Purkey, 2015). The study area was divided into 55 basins, sub-basins and micro-basins, together with their respective areas and percentage distributions (in terms of land cover), to model their respective hydrology. Four main basins were identified: La Samaria Creek (22.4 km^2), La Nona Creek (40.9 km^2), San Francisco River (86.6 km^2) and Campoalegre River (436.1 km^2). The San Francisco River basin contains the Sardinas Creek sub-basin. Within the Campoalegre River basin are five sub-basins: La Cristalina Creek (28.5 km^2), Santana Creek (9.2 km^2), Campoalegrito River (37.2 km^2), La Estrella Creek (48.0 km^2) and San Eugenio River (124.2 km^2). Within the La Estrella Creek sub-basin is the Granizales Creek micro-basin (5.4 km^2), and within the San Eugenio River sub-basin are the La Leona Creek (6.2 km^2) and San Ramon River (26.6 km^2) micro-basins. La Samaria Creek, La Nona Creek, San Francisco River and Campoalegre River are tributaries of the Cauca River, one of the main rivers in Colombia.

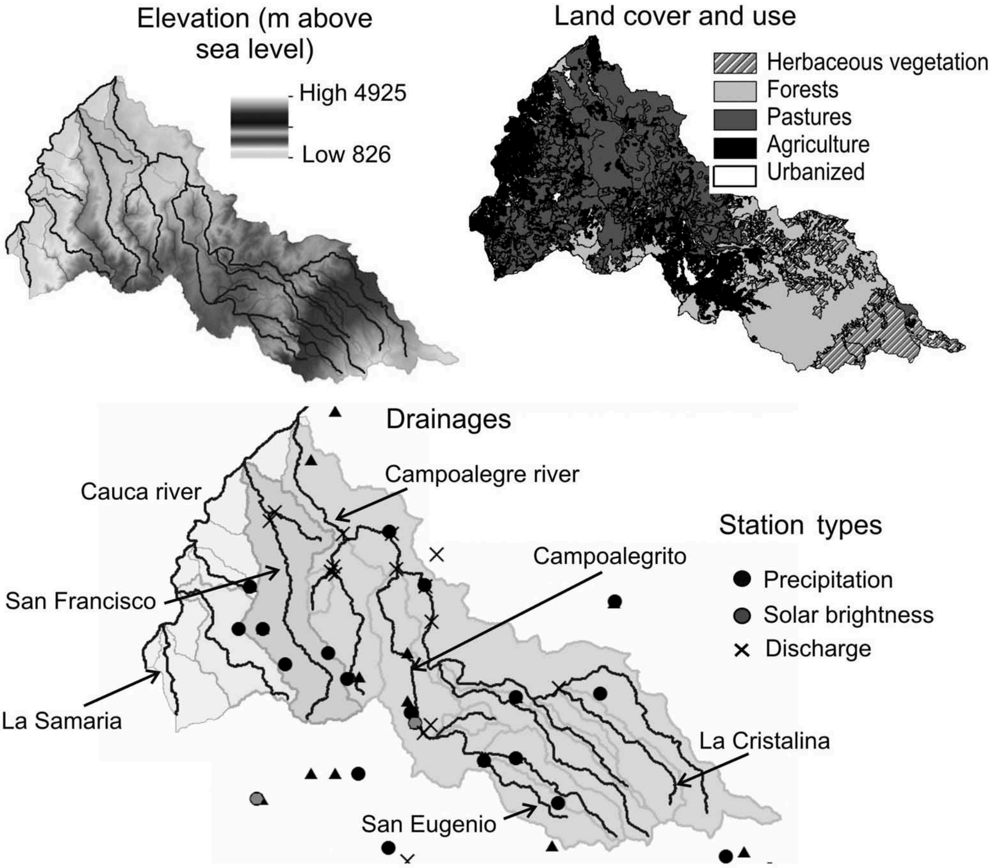

Figure 3. Maps collected for the study area.

Another factor in the water supply is two water transfers: from the Chinchiná River basin into the Campolaegre River and, within the study area, from the Campoalegre River to La Esmeralda Creek. Both transfers occur as a result of CHEC intakes (these transfers were considered in the hydrological model, as shown in Figure 4).

Using both graphical methods (dispersion diagrams, box plots, normality graphs) and quantitative methods (parametric and non-parametric tests, setting the level of significance at 0.05%), the seasonality, consistency and homogeneity of each time series of precipitation, temperature and streamflow were evaluated.

Water demand

Human, hydroelectric, agricultural, livestock, industrial, aquaculture and recreation water demands were characterized, together with their respective pipelines or derivations, reservoirs and return flows (Figure 4 shows the foremost water demands, in terms of quantity, although in WEAP, all those in this list were modelled).

Water demands for human consumption were characterized by integrating water sources, aqueduct users and system losses (conduction and distribution). Projections of current and future demand were made using an exponential method, employing the

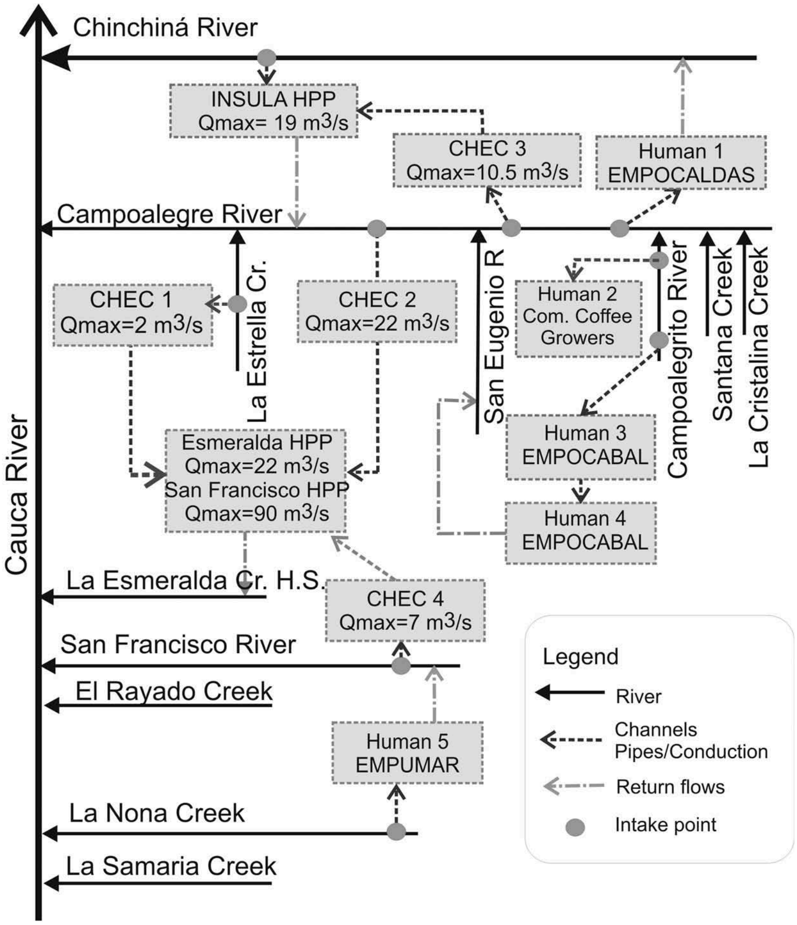

Figure 4. Water intakes and return flows for the most significant water demands for human and hydropower water use.

average growth rate estimated by the National Administrative Department of Statistics (Departamento Administrativo Nacional de Estadística [DANE]), which was 5.4% and 1.9% for Risaralda and Caldas, respectively, in 2015–2020 (DANE, 2013). The maximum diverted flow was set in accordance with the capacity of each intake, losses (obtained from volumes of water produced and volumes of water billed, and then increased by 10% to include adduction and conduction losses), and the average annual consumption per subscriber (Aguas y Aseo de Risaralda SA ESP, 2015; Alzate Ospina, 2011; Corporacion Autonoma Regional de Risaralda and Corporacion Autonoma Regional de Caldas, 2009).

A comprehensive analysis was carried out for each demand node, both spatially and temporally. Also, due to the high levels of tourism and commercial activity in Santa Rosa de Cabal, water use of the subscribers of the Sanitary Works Company of Santa Rosa de Cabal (Empresa de Obras Sanitarias de Santa Rosa de Cabal, EMPOCABAL) was increased by a conservative 20%, based on projections using the exponential method, to capture the dynamics of its transient population. The main users of aqueducts in the study area (shown in Figure 4) were the Sanitary Works Company of Caldas (Empresa de Obras

Sanitarias de Caldas, EMPOCALDAS), the Departmental Committee of Coffee Growers, EMPOCABAL, and the Public Companies of Marsella (Empresas Públicas de Marsella, EMPUMAR). EMPOCALDAS and EMPOCABAL used water from the Campoalegre River. EMPOCABAL had two intakes from the Campoalegrito River. EMPUMAR used water from the San Francisco River (five intakes). These users are detailed in Table 1, together with losses in each aqueduct, customers served, hydraulic capacities and return flows.

To assess hydropower demand, the Ínsula, Esmeralda and San Francisco HPPs were included in the model (Central Hidrolectrica de Caldas, 2013) (Table 2). Unlike what is expected from hydropower generation, the demand for this use is consumptive, due to water transfers to other water sources outside the study area. The Ínsula HPP captures water from the Campoalegre River and the transfer from the adjacent basin of the Chinchiná River and discharges it into the Campoalegre River. The Esmeralda HPP, which is downstream, captures water from the Campoalegre River and La Estrella Creek and discharges it into the San Francisco reservoir. The San Francisco HPP, in the San Francisco reservoir, discharges its water into the Cauca River. The main water intake for the San Francisco HPP is from the Campoalegre River.

Other minor water concessions were granted for human consumption, recreation, aquaculture, industrial, agricultural and livestock water uses (Corporacion Autonoma Regional de Risaralda and Corporacion Autonoma Regional de Caldas, 2009). A total of 41 demand sites were included in the model, with constant water consumption and flow granted following the water concession. Table 3 shows the water flow provided, per concessions and the number of demand sites. It also shows water-use type and total water used, as included in the WEAP model.

Small water users in the agricultural and livestock sectors were also added into the model by considering the land cover classified as permanent crops (coffee) and pasture.

Table 1. Demand characterization of the principal demand sites for human water consumption, based on information provided by each major water user.

Site	1	2	3	4	5
Service enterprise	EMPOCALDAS	Departmental Committee of Coffee Growers of Caldas	EMPOCABAL	EMPOCABAL	EMPUMAR
Source of water supply	Campoalegre River	Campoalegre River	Campoalegrito River	San Eugenio River	La Nona Creek
Users served	13,265	881	23,097	21,320	3,505
Maximum annual water use (m^3 per user)	284	228	242.7	224	252
Maximum loss rate (%)	35.4	70	42	42	70
Maximum concessioned water flow (m^3/s)	0.19	n/a	0.50	0.10	0.05
Hydraulic capacity of the intake (m^3/s)	0.19	n/a	0.55	0.84	0.42

Table 2. Demand characterization for hydropower plants.

Hydropower plant	Insula	Esmeralda	San Francisco
Maximum water flow (m^3/s)	19	22	90
Capacity (MW)	19	30	135
Source of water	Chinchiná River, Cameguadua Creek, Campoalegre River	Campoalegre River, La Estrella River	La Esmeralda diversion water discharge, San Francisco River

Table 3. Water demand following water concessions.

Water use	Concessioned water flow (m^3/s)	Number of demand sites
Human	0.080	27
Recreation	0.026	3
Aquaculture	0.023	4
Industrial	0.010	1
Agricultural	0.010	4
Livestock	0.003	2
Total	0.152	41

The water demand for livestock use corresponded mainly to cattle, whose need for water (in litres per day) represented 17% of their weight (Steinfeld et al., 2009). The standard measurement used was livestock units, where 1 livestock unit represents one 450 kg animal (Anzola Vásquez, Durán Muriel, Rincón Solano, Martínez Román, & Restrepo Vélez, 2014). The Colombian national average carrying capacity was taken to be 0.5 livestock units per hectare (FEDEGAN, 2012), implying total water consumption of 38.25 litres per day per hectare. For the pasture area of approximately 11,000 ha, this amounts to 150,000 m^3 per year.

The water demand for agricultural use, essentially the water consumption for coffee processing, was estimated through assessment of the permanent crop area. The wet (conventional) method was taken as the practice employed in the area to produce dry parchment coffee (Rodriguez Valencia, Sanz Uribe, Oliveros Tascon, & Ramirez Gomez, 2015). Production per hectare was based on reports in the 3rd National Agricultural and Livestock Census (DANE, 2013). The analysis also considered the distribution of water consumption over the year, which in the central zone of Colombia occurs in two crop cycles. The main harvest is from September to December, and the second is in April and May (Rodriguez Valencia et al., 2015). The main harvest represents 75% to 85% of annual production (Rendon, Arcila, & Montoya, 2008). About 1 tonne of coffee is produced per hectare (DANE, 2013), and conventional processing requires 40 litres per kilogram of dry parchment coffee (Rodriguez Valencia et al., 2015). This implies annual water consumption of 42 m^3/ha. The area covered by permanent crops was approximately 15,000 ha, implying a water need of 640,000 m^3 per year.

Environmental flow is the volume of water necessary (in terms of quality, quantity, duration and seasonality) for the maintenance of aquatic ecosystems and the development of the socio-economic activities of users downstream (Presidencia de la República, 2010). Given that the model time frame was monthly, the environmental flow was estimated simply as 25% of the lowest average monthly flow (MAVDT, 2004). To preserve the seasonality of the water flow, the environmental flow was set not as a constant number but as a monthly percentage: the ratio between the estimated environmental flow and the multi-year monthly average flow. To estimate average flows, the model was run without consideration of demand, to determine natural flows.

In total, WEAP demands corresponded to 91 demand nodes, with their respective driving elements and return flows (for demands with available information), which resulted in a total of 13 return flows added to the WEAP model.

The integrated model for water supply and demand

Following the processing of hydroclimatic data, the supply and demand components were entered into the model, so as to obtain an integrated model for water supply and demand in WEAP. The data were connected to each element in a schematic representation of the study area. The historical period considered from 1989 to 2015 was used to calibrate and validate the WEAP model. Then projections were made from the 2018 baseline to 2048. The model was evaluated for goodness of fit, comparing simulated to observed streamflow in the five streamflow gauges. For the instrumented basins, it was possible to calibrate and validate simulated flows in the model.

To calibrate the model, five streamflow gauges were used, which were in the San Eugenio River (La Reina gauge), La Estrella Creek (Estrella Suma gauge), Campoalegre River (Mi Casita and Tarapacá gauges) and San Francisco River (San Francisco gauge). These were in the lower part of the basins, above the water bodies in which the CHEC had water intakes. For water bodies included in the model that did not have streamflow gauges, streamflows were estimated with the hydrological model, using the same parameters as instrumented basins. After having calibrated and validated the model, and under the assumption that the historical climate would repeat cyclically in the future, the baseline projection (2018) was run for 2019 to 2048 (30 years). This generated a database through the extraction of results for water demand and water supply from WEAP. The approach selected to evaluate vulnerability was to compare water demand to water supply and to check the level of intervention and coverage of aqueducts. Level of intervention was defined as the relationship between natural flows at the mouth of the river, which are the simulated flows without considering water demands, and final flows, which are the simulated flows considering water demands, at the mouth of the river. This accounted for all intake that was not returned to the river, signifying an intervention in the natural river conditions. ‘Coverage’ was defined as the ability of a river to meet water needs, including ecological flows, and was measured by the percentage of water demand met. Water demands were covered in order of appearance downstream, and not by use as established in Colombian law.

Finally, a vulnerability index was estimated for the baseline and projected periods as the ratio between the water demand (excluding hydropower demands) and the minimum flows at the mouth of the river. The index was expressed as very low (<1%), low (1–10%), medium (11–20%), high (21–50%), or critical (>51%).

Results

The water supply

The goodness-of-fit measures (Table 4) indicate model performance between satisfactory and very good using the Nash-Sutcliffe Efficiency index (NSE), root mean square error (RMSE), percentage of bias (PBIAS) and correlation (*r*) (Moriasi et al., 2007).

Table 4. Goodness-of-fit measures for the hydrological model.

		Mi Casita	Tarapacá	Estrella Suma	San Francisco	La Reina
Calibration (1990–2007)	NSE	0.51	0.51	0.52	0.56	0.56
	RMSE	0.90	1.60	0.60	0.90	1.10
	PBIAS	0.00%	6.60%	−0.60%	−0.40%	−12.90%
	r	0.58	0.60	0.50	0.60	0.70
Validation (2008–2015)	NSE	0.64	0.76	0.63	0.73	0.52
	RMSE	0.93	1.35	0.52	0.78	1.15
	PBIAS	−0.40%	2.90%	8.90%	1.10%	−13.00%
	r	0.60	0.80	0.70	0.70	0.70

In terms of water supply, annual average flows totalled 1.98 m^3/s for La Nona Creek, 4.18 m^3/s for the San Francisco River, and 27.01 m^3/s for the Campoalegre River. Average annual flows in the principal tributaries of the Campoalegre River were 5.59 m^3/s for the San Eugenio River, 1.37 m^3/s for the Campoalegrito River, and 0.6 m^3/s for La Estrella Creek.

In the Campoalegre River, La Estrella Creek and San Francisco River, streamflow at the mouth significantly decreased, due to places where the water was discharged into a different water body (water transfers via HPPs). In the Campoalegre River, this was mainly due to two CHEC water intakes. After the hydropower infrastructure captured the water, it was transferred into the San Francisco reservoir. The highest flow occurred in the section in which the water was discharged after it was turbinated by the Insula HPP. The same situation occurred in La Estrella Creek and the San Francisco River, which both have CHEC water intakes. In the San Eugenio River and Campoalegrito River, there was an EMPOCABAL water intake in each stream. Finally, in the upper part of La Nona Creek, there were five EMPUMAR water intakes, which supply the urban centre of Marsella; this water was discharged into the San Francisco River.

Water demand

The most significant user in the study area, concerning the water flows required, was CHEC (hydrogeneration) for the Ínsula, Esmeralda and San Francisco HPPs, which represented 97.36% of net consumption (water requirement before losses) in 2018. This was followed by human consumption (2.28%), represented by EMPOCABAL (1.55%), EMPOCALDAS (0.29%), EMPUMAR (0.08%), the Departmental Committee of Coffee Growers of Caldas (0.02%) and 27 users with water concessions (0.31%). The remaining 0.36% of the total water demand was distributed among recreational (0.11%), aquaculture (0.11%), industrial (0.09%), agricultural (0.04%) and livestock demands (0.02%). Therefore, in this document, only hydropower and human use results are shown.

As shown in Figure 5, hydropower use was highest in 2018. For the last simulated year (2048), hydropower remained the sector with the highest demand, but due to population growth, it decreased to 88% of total gross demand.

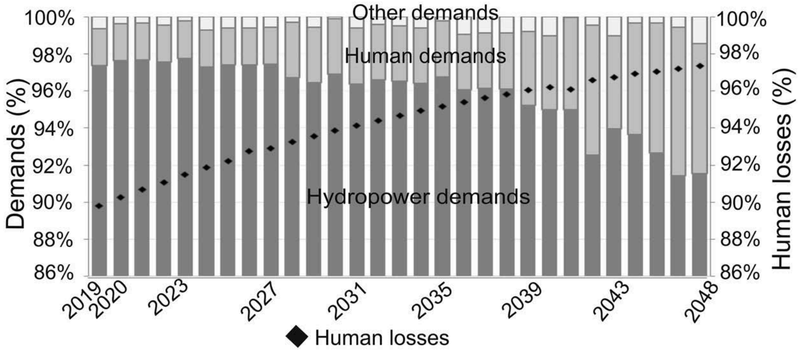

Figure 5. Accumulated net water demand and losses by water use.

Despite the predominance of hydroelectric demand, human demands raised concerns, owing to problems generated by water losses, which limited supply. Losses in 2018 were 0.4 m^3/s and were mainly from human use (89.81%); 68.75% of the total came from the EMPOCABAL demand node. At the end of the future modelling period (2048), losses increased to 1.7 m^3/s, and 97.34% corresponded to human use (Figure 5).

Losses continued to represent approximately 70% of the net demand for human and domestic supplies, and their magnitude continued to increase over the years. The WEAP model characterized the spatial distribution of water uses and demands, which enabled the identification of representative users by basin. In the Campoalegre River basin, 91% of net demand corresponded to hydropower use, and 98% of losses corresponded to human use. In the La Nona Creek basin, the most representative use was human, which likewise represented 99% of losses. In the San Francisco River basin, 99% of net demand corresponded to hydropower use, and losses were mainly due to human use in concession demand nodes (44%) and agriculture (21%).

Average monthly turbinated flows were 20 m^3/s (min. 12.4 m^3/s, max. 22.7 m^3/s) at the Esmeralda HPP, 16.8 m^3/s (min. 11.4 m^3/s, max. m^3/s) at the Ínsula HPP, and 24.5 m^3/s (min. 13.6 m^3/s, max. 32.8 m^3/s) at the San Francisco HPP. On average, the Esmeralda HPP operated at 93% capacity (min. 59%, max. 100%), the Ínsula HPP at 85% (min. 58%, max. 100%), and the San Francisco HPP at 27% (min. 14%, max. 36%).

Water supply and demand balance

The water supply and demand balance analysis shows that in the baseline year there was little pressure on water resources, despite their small tributaries. But more detailed studies should be pursued. Water intakes for small demands could be upstream in minor creeks, where the water supply would be insufficient.

The principal difficulties with water supply were found in La Nona Creek and the Campoalegre, San Francisco and Campoalegrito Rivers. Pressure on water resources was evaluated in terms of level of intervention (Table 5), supply–demand balance, and aqueduct coverage.

Excepting La Nona Creek, the level of intervention was very high in all basins analyzed, which was cause for concern for water planning and management stakeholders. In the La Nona Creek basin, EMPUMAR water intakes were located in the upper part, where the drainage area was only 2 km^2 (5% of the total area of the basin). Consequently, these water intakes had a significantly weaker water supply. This fact has historically produced local water scarcity. The difference between natural and intervened flows was not significant at the mouth of the creek (Table 5), because downstream of the EMPUMAR intakes, the drainage area covers 95% of the total area of the basin.

In the basins of the Campoalegre and San Francisco rivers, there was a high degree of intervention and the (current) pressure on water resources, because HPP water intakes were present in these main streams. In the Campoalegre River, monthly flows were in the range of 16.1 to 46.1 m^3/s. However, this was reduced by water transfers to other sources by up to 84% at times of minimum water flow, and 54% at maximum flow. In the San Francisco River, flows were reduced by 91% and 74% for minimum and maximum flow, respectively, and in the Campoalegrito River by 79% and 19%, respectively.

Table 5. Level of intervention in each stream.

	Basin	La Nona Creek	Campoalegre river	San Francisco river	Campoalegrito river
	Basin area (km^2)	40.9	436.1	86.6	37.2
Conditions for minimum flows	Flow at the mouth (m^3/s)	0.53	16.11	1.38	0.56
	Flow after intakes (m^3/s)	0.53	2.90	0.13	0.12
	Intakes (m^3/s)	–	13.21	1.25	0.44
	Level of intervention	0	82%	91%	79%
Conditions for average flows	Flow at the mouth (m^3/s)	1.98	27.01	4.18	1.37
	Flow after intakes (m^3/s)	1.98	5.40	0.37	0.81
	Intakes (m^3/s)	–	21.61	3.81	0.56
	Level of intervention	0	80%	91%	41%
Conditions for maximum flows	Flow at the mouth (m^3/s)	5.67	46.14	10.8	2.92
	Flow after intakes (m^3/s)	5.66	21.08	2.81	2.37
	Intakes (m^3/s)	0.01	25.06	7.99	0.55
	Level of intervention	0	54%	74%	19%

Even so, the supply–demand water balance (Table 6) showed that, although the level of intervention was high in all basins, according to Colombian regulations the pressure on water resources was low (<10%) in all watersheds except for the Campoalegrito River. In that river, the available water supply was insufficient, with a water balance of 131%.

The future performance of the water supply–demand balance was also analyzed (Table 6). This indicated that the watersheds with uncontrolled human consumption were the most threatened. For the Campoalegrito River, pressure on the stream increased to levels at which the water deficit was unsustainable. In 2048, the balance was 586%, showing an exponential increase due to population growth and aqueduct losses. Another small watershed analyzed was the La Nona basin, an area similar to the Campoalegrito basin. Water use increased by 41 percentage points (from 11% in 2018 to 52% in 2048), a very steep increase, pushing it from the moderate-pressure category to the very-high-pressure category.

In the Campoalegre basin, the largest watershed, water demands increased 17 percentage points (from 6% in 2018 to 23% in 2048), moving it from the low-pressure category to the high-pressure category. This was the most significant category change among the four watersheds analyzed.

Table 6. Supply–demand water balance for minimum conditions.

		Water demand without hydropower (m^3/s)			Water balance		
Main water body	Basin area (km^2)	2018	2048	Minimum flow at the mouth of the river (m^3/s)	2018	2048	Vulnerability index 2019/2048
La Nona Creek	40.9	0.06	0.28	0.53	11%	52%	Medium/critical
Campoalegre River	436.1	1.02	3.69	16.11	6%	23%	Low/high
San Francisco River	86.6	0.02	0.03	1.38	1%	2%	Very low/very low
Campoalegrito River	37.2	0.73	3.28	0.56	131%	586%	Critical/critical

In contrast, the San Francisco basin, another small watershed, showed an increase of only one percentage point (from 1% in 2018 to 2% in 2048), despite being the water body with the highest level of intervention (Table 6).

When hydropower use was considered, the water balance in the Campoalegre River increased to 237%, and that of the San Francisco River to 652%. Since hydropower water use was a lower priority, it adapted to water supply availability after the water had been distributed between other water uses.

Finally, the water coverage for the two main human users in the study area, EMPOCABAL (the Campoalegrito and San Eugenio Rivers) and EMPOCALDAS (the Campoalegre River), was 100% for the baseline year (2018). However, a significant threshold was projected for EMPOCABAL in 2032, when coverage began to diminish, through 2048, when it would reach a scant 40% (Figure 6). For EMPOCALDAS, water coverage began to decrease in 2042, dropping to 90% by 2048 (Figure 6). The coverage losses for EMPOCABAL and EMPOCALDAS were mainly due to population growth, as well as current system losses and annual water use rates, which both exceed the limits set by the Technical Regulation of Drinking Water and Basic Sanitation Sector (Ministerio de Desarrollo Económico, 2000). Other demands for water did not cause such significant pressure on water resources.

We computed a medium and critical vulnerability index for La Nona Creek and the Campoalegrito River, respectively, in the baseline year. Therefore, basin management plans require prioritization. These basins are the smallest, and therefore the most heavily affected. Also, according to projections, the situation worsens considerably in 2048, with La Nona Creek moving from medium vulnerability to critical, mainly due to losses in the water supply infrastructure for domestic use. The Campoalegre River changes from low vulnerability to high, due to higher losses caused by rising domestic water demand. This will exert great pressure on water resources.

The Campoalegrito River remained in critical condition during the period analyzed. This river requires immediate attention and the application of both short-term and long-term strategies. It is important to note that the entire region was strongly influenced by climate variability factors from the baseline to the end of the future projection.

Discussion and conclusions

The Colombian Andes is a rainy place. Yet water stress is present in most watersheds during periods influenced by ENSO and ITCZ. This study has investigated the vulnerability of the study area. Baseline findings and future projections include the effects of climate variability.

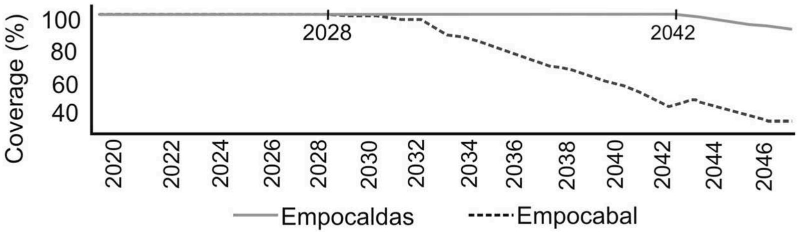

Figure 6. Results of the coverage of the main human water use demands.

The water balance of the Campoalegre River basin was assessed to quantify water supply and demand, assess their relationship and evaluate the vulnerability of water demand coverage. The model enabled the identification of areas with high water use, as well as possible ways to reduce water vulnerability.

IDEAM performs a national water evaluation every four years, using an aggregated approach. The 2014 evaluation estimated the ratio between water demand and supply for the entire study area at 15.18% (Minambiente and IDEAM, 2014), or moderate pressure. We disaggregated the demand and supply, by basin, in a monthly representation of future projections (2019–2048). This complements earlier studies with data which until now were not available. Those water bodies under the greatest pressure on water resources were the Campoalegrito River (demand at 131% of supply in 2018, and 586% of supply in 2048) and La Nona Creek (11% in 2018, 52% in 2048). In both cases, human water use is dominant and exacerbates water conflicts, with a water coverage loss of 60%. In contrast to IDEAM studies, we find that in 2018 the largest watersheds (the Campoalegre and San Francisco basins) faced little pressure, while the smallest (the La Nona and Campoalegrito basins) faced moderate and very high pressure, respectively.

However, projections are more worrisome, as they indicate insufficient water to meet the projected demand, which could result in rationing and water-use conflicts. In the Campoalegre and San Eugenio Rivers, the high pressure on water resources is due to the use of water for hydropower. The environmental authority should establish environmental flows under current environmental regulations, which would force the HPPs to reduce water flow through the turbines.

The WEAP model also enables a disaggregated analysis of user demand to study vulnerability. Water balance (ratio between water supply and demand) studies are generally carried out in an aggregate form in water basins, with an accumulation of water demand and measurement of streamflow at the mouth of the basin. In those cases, pressure on the water resources or conflicts over water uses may not be identified. Such is the case in the Campoalegre River basin in the present day. Water demand, overall, is far less than supply (6% of supply in 2018, and 23% in 2048). But disaggregated analysis shows that EMPOCALDAS will see its water demand coverage reduced from 100% to 90%, which implies rationing. These results highlight the importance of disaggregated studies, using tools such as WEAP.

The water demand coverage of the municipal aqueducts in the study area could reach a critical state unless strategies are implemented to reduce demand. In particular, strategies to address losses (conduction and distribution) and the annual water use rate will be vital. These may include infrastructure improvement and maintenance, control of unidentified users, awareness campaigns to reduce water use, higher-efficiency washing machines and toilets, and conservation and restoration strategies that increase the water supply.

This analysis and the tools generated thereby can help decision makers identify potential future conflicts over water use, as well as the need to ration, should it be caused by water stress. Thus, strategies may be proposed for the achievement of secure water supply in the basins. Our results should help environmental authorities make informed decisions and thus contribute to better water governance.

The validated and calibrated WEAP model could include climatic and non-climatic scenarios, which enable users to evaluate the impact of adaptation measures. The next steps in this process are to identify strategies and uncertainties, with the help of key players, and to continue exploring future scenarios and strategies to reduce vulnerability.

Once optimal strategies are identified, financing must be sought for their implementation. The application of the water quality component of the model must also be prioritized.

Water resource management needs to be done recognizing the activities that take place in the basin, which is why those directly involved in the development of planning tools (stakeholders) must participate. These players include government entities, communities, industries, academia and decision makers.

Short-term measures must be taken for those basins in a state of a high or critical vulnerability. These measures might include loss-reduction programmes, education on efficient water use, and strengthening the governance and administration of the companies that provide water services. They should also include long-term strategies for infrastructure improvement, recovery through reforestation, and water harvesting, as well as the combined use of water resources (both underground and surface water).

Finally, as climate variability, as shown in ENSO and ITCZ, increases vulnerability, regional environmental authorities, politicians and local planners must implement mitigation strategies, because changes will affect the entire region. In the past, the absence of these strategies has been yet another cause of vulnerability. There is a constant need to learn and to involve communities in this education, to address the evolving impacts on the Campoalegre basin.

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References

Aguas y Aseo de Risaralda SA ESP. (2015). *Formulación de Planes Maestros de Acueducto y Alcantarillado de Municipios de Risaralda* [Formulation of master plans for aqueducts and sewer systems of the municipalities of Risaralda]. Bogota, Colombia: Aguas y Aseo de Risaralda SA ESP.

Alzate Ospina, D. L. (2011). *Diseños Para el Mejoramiento de los Sistemas de Captacion y Potabilizacion de Agua del Municipio de Marsella*. Pereira, Colombia: Marsella Municipality.

Anzola Vásquez, H., Durán Muriel, H., Rincón Solano, J. C., Martínez Román, J. L., & Restrepo Vélez, J. (2014). El Uso Eficiente de los Forrajes Tropicales en la Alimentación de los Bovinos [The efficient use of tropical Forages in cattle feed]. *Revista Ciencia Animal*, *7*, 111–132.

Babel, M. S., & Jensen, J. R. (2010). Regional workshop on water saving irrigation practices in rice-based canal systems, Bangkok, Thailand, 8–9 October 2009. *International Journal of Water Resources Development*, *26*(3), 513–515. doi:10.1080/07900627.2010.489302

Bedoya Soto, J. M., Poveda, G., Trenberth, K. E., & Vélez Upegui, J. J. (2019). Interannual hydroclimatic variability and the 2009–2011 extreme ENSO phases in Colombia: From Andean glaciers to Caribbean lowlands. *Theoretical and Applied Climatology, 135*(3–4), 1531–1544. doi:10.1007/s00704-018-2452-2

CARDER. (2011). Land cover and soil map. Corporación Autónoma Regional de Risaralda.

Central Hidrolectrica de Caldas. (2013). *Informe de Presentación al Mercado Reasegurador* [Report of the presentation to the reinsurance market]. Central Hidrolectrica de Caldas.

Claure Pereira, S., Portocarrero Lau, C., & Valencia Quintero, J. (2015). *Taller de Intercambio de Experiencias entre Consejos de Cuenca de Perú, Colombia y México* [Experience exchange workshop between basin councils of Peru, Colombia and Mexico]. Cartagena, Colombia. Retrieved from http://www.para-agua.net/file/ralcea/15-10-15/Proyecto PARA-Agua - USAID.pdf

CORPOCALDAS. (2011). *Land Cover and Soil Maps. 1:25:000*.

Corporacion Autonoma Regional de Risaralda and Corporacion Autonoma Regional de Caldas. (2009). *Plan de Ordenamiento y Manejo de la Cuenca del Río Campoalegre* [Campoalegre river basin management plan]. Pereira, Colombia.

Corporacion Autonoma Regional del Rio Grande de la Magdalena and IDEAM. (2001). *Estudio Ambiental de la Cuenca Magdalena-Cauca y Elementos para su Ordenamiento Territorial. Resumen Ejecutivo [Environmental study of the Magdalena-Cauca basin and elements for its territorial management. Executive summary]*. Bogota, Colombia: Corporacion Autonoma Regional del Rio Grande de la Magdalena and IDEAM.

DANE. (2013). *Geoportal del 3er Censo Nacional Agropecuario (GeoCNA)* [Geoportal of the 3rd National Agricultural Census].

Droogers, P., & Bouma, J. (2014). Simulation modelling for water governance in basins. *International Journal of Water Resources Development*, *30*(3), 475–494. doi:10.1080/07900627.2014.903771

FAO. (2003). *Review of world water resources by country*. Rome: FAO. Retrieved from http://www.fao.org/tempref/agl/AGLW/ESPIM/CD-ROM/documents/5C_e.pdf

FEDEGAN. (2012). *Analisis del inventario ganadero colombiano. Comportamiento y variables explicativas [Analysis of the Colombian livestock inventory. Behavior and explanatory variables]*. Colombia: Federación Colombiana de Ganaderos. Retrieved May 15, 2018, from http://www.fedegan.org.co/publicacion-presentaciones/analisis-del-inventario-ganadero-colombiano-comportamiento-y-variables

Goes, B. J., Howarth, S. E., Wardlaw, R. B., Hancock, I. R., & Parajuli, U. N. (2016). Integrated water resources management in an insecure river basin: A case study of Helmand River basin, Afghanistan. *International Journal of Water Resources Development*, *32*(1), 3–25. doi:10.1080/07900627.2015.1012661

Guzmán-Arias, I., & Calvo-Alvarado, J. (2013). Planificación del recurso hídrico en América Latina y el Caribe [Planning Water Resources in Latin America and the Caribbean]. *Revista Tecnología En Marcha, 26*(1), 3. doi:10.18845/tm.v26i1.1117

MADS. (2010). *Política Nacional para la Gestión Integral del Recurso Hídrico*.

MAVDT. (2004). *Resolucion 865*.

Minambiente and IDEAM. (2014). *Estudio Nacional del Agua 2014*.

Ministerio de Ambiente y Desarrollo Sostenible de Colombia. (2010). *Política Nacional para la Gestión Integral del Recurso Hídrico* [National policy for the integrated water resources management].

Ministerio de Desarrollo Económico. (2000). *Reglamento Tecnico del Sector de Agua Potable y Saneamiento Basico RAS-2000* (p. 184). Retrieved from http://cra.gov.co/apc-aa-files/37383832666265633962316339623934/5._Sistemas_de_potabilizacion.pdf

Moriasi, D. N., Arnold, J. G., Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the American Society of Agricultural and Biological Engineers*, *50*(3), 885–900. doi:10.13031/2013.23153

NASA. (2013). *NASA shuttle radar topography mission global 1 Arc second. NASA EOSDIS Land Processes DAAC*.

OECD. (2015). Governance challenges and suggested tools for the implementation of the water-related sustainable development goals. *UN-Water Annual International Zaragoza Confrence, Water and Sustainable Development From Vision to Action* (pp. 1–10). OECD. Retrieved from https://www.un.org/waterforlifedecade/waterandsustainabledevelopment2015/pdf/Governance_OECD_Tool_paper_final.pdf

Pahl-Wostl, C. (2007). Transitions towards adaptive management of water facing climate and global change. *Water Resources Management, 21*(1), 49–62. doi:10.1007/s11269-006-9040-4

Polpanich, O.-U., Lyon, S. W., Krittasudthacheewa, C., Bush, A. L., & Kemp-Benedict, E. (2017). Modelling impacts of development on water resources in the Huai Sai Bat sub-basin in North-Eastern Thailand with a participatory approach. *International Journal of Water Resources Development*, *33*(6), 1020–1040. doi:10.1080/07900627.2017.1322940

Poveda, G. (2004). La Hidroclimatología de Colombia: Una Síntesis desde la Escala Interdecadal hasta la Escala Diurna. *Revista Academia Colombiana de Ciencias*, *28*(107), 201–222. doi:10.18257/issn.0370-3908

Presidencia de la República. (2010). Decreto 3930 sobre Usos del Agua. Diario Oficial No.47873 de La República de Colombia, Bogotá.

Purkey, D., & Escobar, M. (2015). *Ríos del Páramo al Valle: Creando Capacidad de Adaptación en la Planeación de Recursos Hídricos. Reporte Final del Proyecto* [Rivers from moorland to valley: Creating adaptation capacity in the planning of water resources. Final report]. Bogota, Colombia: USAID.

Purkey, D. R., Joyce, B., Vicuna, S., Hanemann, M. W., Dale, L. L., Yates, D., & Dracup, J. A. (2007). Robust analysis of future climate change impacts on water for agriculture and other sectors: A case study in the Sacramento valley. *Climatic Change*, *87*(S1), 109–122. doi:10.1007/s10584-007-9375-8

Rendon, J. R., Arcila, J., & Montoya, E. C. (2008). Estimacion de la produccion de cafe con base en los registros de floración [Estimation of coffee production based on the flowering records]. *CENICAFE, 59*(3), 238:259. Retrieved from https://www.cenicafe.org/es/publications/arc059(03)238-259.pdf

Rodriguez Valencia, N., Sanz Uribe, J. R., Oliveros Tascon, C. E., & Ramirez Gomez, C. A. (2015). *Beneficio del Cafe en Colombia* [Coffee processing in Colombia]. Chinchina: CENICAFE.

Sieber, J., & Purkey, D. (2015). *WEAP user guide*. Somerville, MA: SEI.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., & Haan, C. (2009). *La Larga Sombra del Ganado, Problemas Ambientales y Opciones* [The long shadow of cattle, environmental problems and options]. Rome: FAO and LEAD.

Stockholm Environment Institute. (2018). *WEAP: Water evaluation and planning system*.

Wilson, G. T. (2016). Book review: Time series analysis: Forecasting and control, 5th edn, by George E. P. Box, Gwilym M. Jenkins, Gregory C. Reinsel and Greta M. Ljung, 2015. *Journal of Time Series Analysis, 37*(5), 709–711. doi:10.1111/jtsa.12194

Yates, D., Purkey, D., Sieber, J., Huber-Lee, A., Galbraith, H., West, J., … Rayej, M. (2009). Climate driven water resources model of the Sacramento Basin, California. *Journal of Water Resources Planning and Management, 135*(5), 303–313. doi:10.1061/(ASCE)0733-9496(2009)135:5(303)

Yates, D., Sieber, J., Purkey, D., & Huber-Lee, A. (2005). WEAP21: A demand-, priority-, and preference-driven water planning model: Part 1: Model characteristics. *Water International*, *30*(4), 487–500. doi:10.1080/02508060508691893