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Multi-criteria analysis applied to the selection of drinking water sources in developing countries: A case study of Cali, Colombia

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Abstract

Guaranteeing a safe and continuous drinking water supply for the city of Cali, Colombia, has become a concern for the water company of Cali, the environmental authorities, universities, and entities involved in the water resource. The progressive deterioration of the city's water sources has led to a search for future water sources and/or technologies in order to ensure high water quality standards at minimal costs. This paper describes a variety of problems occurring in the current water supply system in Cali and gives a description of the alternatives that were considered to solve these problems in the past decades. Multi-criteria analysis was applied to assess alternatives for safe drinking supplies, demonstrating their suitability, during the decision-making process, when constraints arise due to political, community and institutional interests.

Keywords: Drinking water supply, riverbank filtration, multi-criteria analysis, PROMETHEE

Introduction

The high variability of water quality in surface water in Colombia, including the level of risk to human health, is threatening its use as a source for drinking water. Colombia is characterized by its abundance in water resources, where its average water yield exceeds six times the average global water yield and three times the Latin American water yield (IDEAM 2010). However, the availability of water is constrained by the deterioration of its quality. Progressive deterioration of the surface water is mainly caused by rapid urbanization, in combination with a lack of integration between water management and spatial planning. The problem has been exasperated by inappropriate land use, poor protection of the river basins, wastewater and stormwater discharges from municipalities, discharges from domestic and industrial wastewater treatment plants, and also mining, deforestation processes and improper management (van der Kerk 2011).

Multi-criteria analysis applied to urban water management

Multi-criteria analysis (MCA) tools have been widely used in decision-making situations to ensure a drinking water supply, in terms of water quantity and quality, where a diverse range of alternatives is available.

MCA is a decision-analysis tool for dealing with complex decision-making problems with more than a single criterion and involving a variety of stakeholders. As described by Lai et al. (2008), there are various decision-support methodologies available for MCA, which can be classified as follows: elementary procedures (e.g. conjunctive and disjunctive methods); single synthesizing criterion approaches (e.g. Multi-Attribute Utility Theory (MAUT), Multi-Attribute Value Theory (MAVT), Analytical Hierarchy Process (AHP)); outranking methods (e.g. ELECTRE, PROMETHEE, REGIME, NAIADE); and goal or reference point methods (e.g. Goal Programming (GP) and Compromise Programming (CP)).

The selection of the decision-support methodologies depends on the availability of information and its quality (Lai et al. 2008). Jaber and Mohsen (2001) described the development of a decision-support system for the evaluation and selection of potential non-conventional water supply systems in Jordan using the Analytic Hierarchy Process. Domènech et al. (2013) analyzed the compatibility of non-conventional centralized and decentralized water supply technologies in Spain using a social multi-criteria evaluation.

This paper focuses on the development of an MCA framework to assess the alternative that best suits the necessities of the city of Cali, Colombia. That framework is based on the drinking water supply problems suffered there and the external constraints involved in the decision-making structure in developing countries such as Colombia.

A review was carried out in order to pinpoint the most pressing drinking water related issues in Cali. Moreover, additional data collection and analysis were conducted to have a better understanding of the magnitude of the contamination of the Cauca River, which is used as the main water source for the water supply to Cali. The pre-proposed alternatives were evaluated objectively in order to define the more suitability solutions to meet the future water demand of the city.

Materials and methods

This study is divided into two parts: (1) impact of water quality on Cali's current drinking water system; and (2) the application of the MCA tool. The methodology used in each part is described as follows:

(1) The impact of water quality on the functioning of the drinking water system for the city of Cali was reduced to the evaluation of the impacts of the current Cauca River water quality on the Puerto Mallarino WTP because, as described above, it represents the most water coverage for the city. This analysis was based on turbidity and dissolved oxygen (DO) because these parameters correspond to the operational thresholds in the WTP. The

turbidity indicator is related to extreme sediment loads, and the DO is associated to extreme contamination events. Therefore, when any of the mentioned parameters reaches or surpasses the operational thresholds, the WTP may not treat the entering water due to the uncertainty of contaminants in the source water. Other parameters are monitored at the WTP intake and in a station located 4.5 km upstream from the WTP intake (pH, color and electrical conductivity). However, only turbidity and DO are linked to the operational thresholds.

(2) Multi-criteria decision analysis. An inventory was made of the alternatives as previously proposed by the drinking water company (EMCALI EICE ESP), environmental authorities, consultants and universities. The alternatives studied at a pre-feasibility and feasibility level, that by themselves or in combination comply completely with the water demanded by the city, were compared by applying the MCA tool. The water company has considered the alternatives be included as promising solutions, therefore in this study additional alternatives were not proposed. The water demand for the city is expected to reach 11.9 m³/s in 2036. The alternatives were evaluated by projecting the costs until year 2036. However, it must be pointed out that the “useful life” is not the same for all alternatives, since some of them will use existing facilities that may require upgrading. A sensitivity analysis was conducted by applying the MCA under different criteria scenarios.

Study site

Cali is the capital of the Valle del Cauca Department, located in the south-western part of Colombia between the Central Mountain Range and the Pacific Ocean. It is the third most important city in the country, with 560.3 km² of municipal area and a population of approximately 2.5 million people. The city has experienced rapid population growth in the past decades due to its geographic location as the principal urban, cultural, and economic centre in south-western Colombia (Universidad del Valle and UNESCO-IHE 2008).

Drinking water supply system of Cali

The drinking water supply system in Cali is provided by five drinking water treatment plants (WTPs): Puerto Mallarino, Río Cauca, Río Cali, La Reforma and La Rivera (Figure 1), having a total capacity of around 12 m³/s. The distribution system consists of 2,820 km of pipelines having diameters between 3” and 56”, 41 water storage tanks and 16 pumping stations (PDA 2008; Pérez-Vidal et al. 2012). The distribution network is divided into four sectors: High network, Low network, Reforma network and Pance network. In addition, there are four deep wells located in the Aguablanca District: Orquídeas, Naranjos, Guadales, and Desepaz (see Figure 1). The wells, which had a total capacity of 0.6 m³/s (0.15 m³/s each), previously delivered water to a portion of the Low network (normally supplied by Puerto Mallarino and Río Cauca WTPs) during droughts. However, the deep wells are no longer in use.

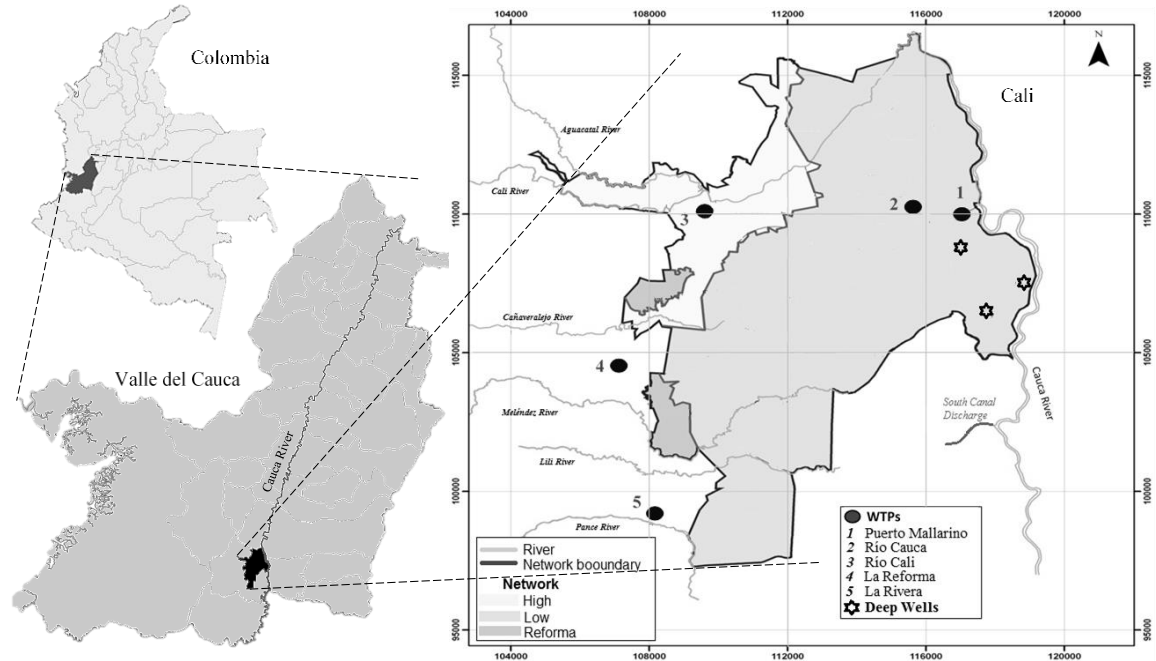


Figure 1. Location of WTPs in the city of Cali, Colombia

Puerto Mallarino and Río Cauca WTPs mainly supply the Low network. However, during drought periods these WTPs partially support the High and Reforma networks as well (see Figure 1 and Table 1). Surface water from the Cauca River is extracted and treated directly by both WTPs. The water quality and quantity from the Cauca, Cali and Meléndez rivers are variable (Universidad del Valle and UNESCO-IHE 2008; PDA 2008). Therefore, when there is a shortage of water at any WTP, Puerto Mallarino and Río Cauca WTPs must compensate for these deficits (Table 1). La Rivera WTP extracts its water from the Pance River, which has good water quality in terms of its physical, chemical and microbiological parameters and is in agreement with Decree 1594/84 (Colombian regulation for water use and residual liquids).

Table 1. Overall description of the water supply system of Cali

WTP	Surface Water Source					Treatment Capacity (m ³ /s)	Mean Production (m ³ /s)	Network Supplied	Coverage (%)
	River	Q _{min} (m ³ /s)	Q _{max} (m ³ /s)	Q _{mean} (m ³ /s)	Water Quality				
Puerto Mallarino	Cauca	48	1260	258.75	Poor	6.6	4.03	Low	56
Río Cauca						2.5	1.53	Low	21
Río Cali	Cali	0.2	193.0	3.80	Good	1.8	1.29	High	17.1
La Reforma	Meléndez	0.3	19	0.82	Poor	1.0	0.37	Reforma	5.7
La Rivera	Pance	0.1	21	1.5	Good	0.034	0.014	Pance	0.2

Note: Instantaneous historical data until December 2013 at WTPs intakes were used as Q_{min} and Q_{max}

Puerto Mallarino and Río Cauca WTPs cover 77% of the city and occasionally the coverage reaches more than 80% of the city: when water flows in Meléndez, when the Cali rivers are too low, and when the Río Cali and La Reforma WTPs are not able to

produce a sufficient water flow. Cali thus relies heavily on the Cauca River as its main source of potable water.

Puerto Mallarino WTP

The WTP Puerto Mallarino is located on the western bank of the Cauca River, in the northeastern part of the city (Figure 1). The plant currently uses a complete train comprising (see Figure 2): (a) a lateral intake; (b) raw water pumping station with six pumps; (c) powdered activated carbon (PAC) dosing in injection lines; (d) two grit chambers with four containers each; (e) two rapid mixing chambers where chlorine (pre-chlorination step) and coagulant (liquid FeCl_3) are added; (f) four compact circular sludge blanket and solid contact reactors where flocculation and settling occur; (g) intermediate chlorination; (h) 24 declining-rate rapid filters (sand and anthracite); (i) pH conditioning where $\text{Ca}(\text{OH})_2$ is added; (j) chlorine disinfection in a 24,000 m³ contact tank; (k) a drinking water pumping station with nine pumps to the distribution network; and, (l) an 80,000 m³ clarified water reservoir.

At the end of 2009, the clarified water reservoir was put into operation to deal with turbidity and contamination events. The reservoir stores clarified water, which is the water coming from the compact circular sludge blanket and solids contact reactors. This allows the mixing of raw water and water from the reservoir during high turbidity peak events (turbidity > 2,500 NTU) and avoids the intake of raw water during contamination events (using only water from the reservoir when DO is in the raw water < 2.5 mg/L).

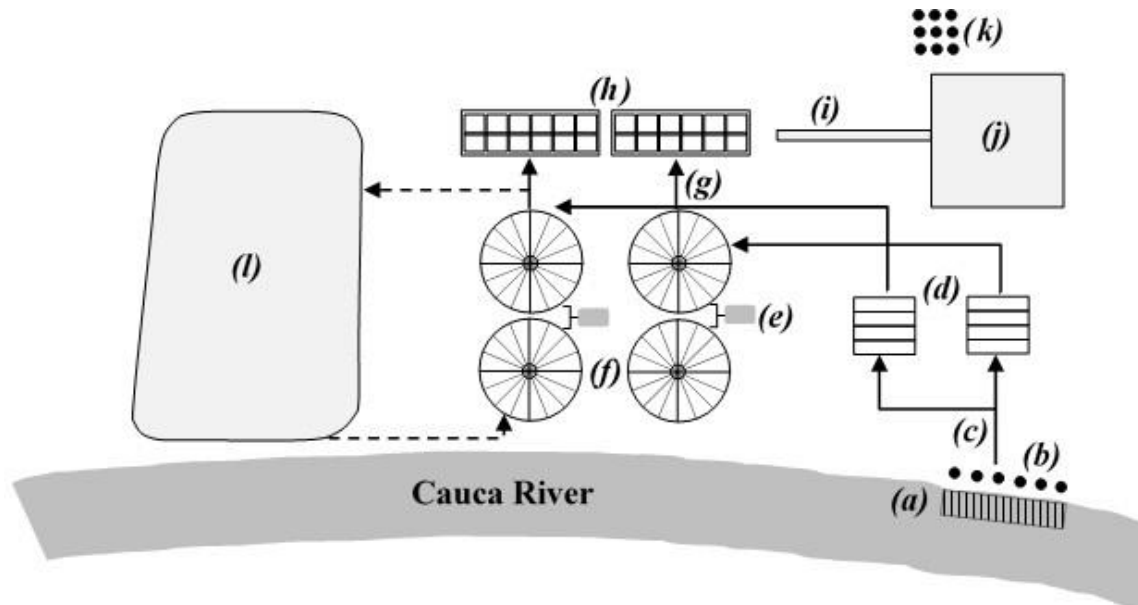


Figure 2. Puerto Mallarino WTP operation units: (a) intake, (b) raw water pumping station, (c) PAC dosing, (d) grit chambers, (e) mixing chambers, (f) clarifiers, (g) intermediate chlorination, (h) filtration, (i) pH conditioning, (j) chlorine disinfection, (k) treated water pumping station, (l) clarified water reservoir

Río Cauca WTP

The Río Cauca WTP accounts for approximately 21% of the city's water demand (Universidad del Valle and UNESCO-IHE 2008; PDA 2008). According to PDA (2008) the WTP currently uses a complete train with solids contact reactors comprised of: a lateral intake; 2 km of pipeline to the WTP; activated carbon dosing in an injection line; one grit removal chamber; one raw water pumping station with six pumps; one distribution chamber to reactors; six reactors for rapid mixing where chlorine (pre-chlorination step) and coagulant (mineral polymer of aluminum) are added and where flocculation and particle settling processes occur; 32 rapid sand filters (only sand) at a constant rate and constant head; chlorine disinfection in a contact tank; pH conditioning where $\text{Ca}(\text{OH})_2$ is added; two chlorine contact tanks; and a drinking water pumping station with five pumps to the distribution network. Its intake is located at a few meters downstream of the intake of Puerto Mallarino WTP.

MCA framework structured for selection of alternatives

MCA was used to evaluate alternative solutions for covering future water demands in Cali based on selected criteria. The selection of these criteria was made by comparing similar frameworks on urban water management (Domènech et al. 2013; Balkema et al. 2002); however, specific issues regarding the problems of this case study, such as current legal and social acceptance, were included. Therefore, the following criteria were selected: investment, O&M requirements, sludge management, environmental impact, vulnerability issues, current legal aspects and social acceptance. A preliminary framework was given to a group of six professionals with senior experience in the water supply sector and from different institutions (universities, environmental authorities and independent consultants) in Cali. The group was asked to review the framework and to evaluate each criterion separately, which resulted in a weighting factor according to the given situation. The final criteria selection and weighting was realized as objectively as possible, in agreement with the concept given by the group of professionals who individually provided input. The inventory of alternatives was also given to the group, who then graded the criteria individually, according to the resulting framework (Table 2).

Table 2 displays the framework for the assessment of the alternatives, including the criteria with their respective descriptions, assigned weight and grading scale, which was the result of the professionals' judging. Political and stakeholder interests, especially in developing countries such as Colombia, are key factors in influencing decision-making. Obtaining environmental permits for the execution of major projects such as dams can, therefore, take many years, due in part to bureaucratic procedures and obstacles placed by both legally settled communities and the slums that are frequently located on the banks of rivers and other protected zones (iDMC and NRC 2011). Hence, the legal and social acceptance criteria (weighting factor 20) became important in the use of the MCA for this case study. Additionally, O&M and sludge disposal are the main processes leading to costly water production in the city of Cali. The costs are linked to chemical usage, sludge production and its treatment, and energy consumption due to pumping actions (Universidad del Valle and UNESCO-IHE 2008), making O&M of crucial importance to the selection of alternatives for Cali.

1 Table 2. Multiple criteria framework to assess the selection of the alternatives

Criteria	Indicator	Description	Weight	Grading*
Investment	Investment Costs	Initial investment based on the construction of dams, WTPs, wells, reservoirs, adjustment of existing facilities, etc.	10	Quantitative scale - linear function
Operation & Maintenance	Raw Material	Use of chemicals for water treatment (e.g. activated carbon, chlorine, coagulant, polymer, lime, etc.)	6	Impact ¹
	Energy Requirements	Involves consumption of energy during water abstraction, treatment and distribution	6	Impact ¹
	Staff Requirements	Requirement of specialized staff and number of employees needed during water abstraction and treatment	4	Impact ¹
	Hydraulic	Comprises washing of reactors and other facilities, backwashing of filters, O&M of conducting structures, purges, etc.	2	Impact ¹
	Electro-mechanical	Maintenance of equipment in terms of electrical, electronic and mechanical features	2	Impact ¹
Sludge Management	Sludge Production	Sludge/waste production during water treatment	4	Impact ¹
	Sludge Treatment and Disposal	Treatment needed to transform the sludge/waste produced during water treatment. This considers special sludge (organic matter, micro-pollutants, iron and manganese precipitates, etc.). In addition, treated sludge disposal requirements are considered	6	Impact ¹
Environmental Impact	Soil	Comprises alteration of soil structure, subsidence phenomena, soil movement, chemical composition, etc.	2	Impact ¹
	Air	Contamination of air during operation. Its effect during construction is also considered with a low weight when grading	0.5	Impact ¹
	Water	Contamination of water during operation. Its effect during construction is also considered with a low weight when grading	2	Impact ¹
	Noise	Noise production during operation. Its effect during construction is also considered with a low weight when grading	0.5	Impact ¹
	Landscape	Landscape modification during construction and operation	2	Impact ¹
	Wildlife	Wildlife migration	3	Impact ¹
Vulnerability	Shock Loads	Robustness and flexibility of the system facing shock loads of contaminants	3.5	Impact ¹
	Flood	Robustness and flexibility of the system facing flood events	2	Impact ¹
	Drought	Robustness and flexibility of the system facing drought events	3	Impact ¹

Criteria	Indicator	Description	Weight	Grading*
	Terrorism	Robustness and flexibility of the system facing terrorism activities	1	Impact ¹
	Earthquakes	Robustness and flexibility of the system facing earthquake events	0.5	Impact ¹
Legal Aspects	Current Legal Acceptance	Considers the legal procedures in terms of time, ease/difficulty, acceptance by current normalcy	20	Impact ¹
Social Acceptance	Social Acceptance	Contemplates obstacles imposed by society, land negotiations with communities.	20	Impact ¹

* A qualitative scale was used for all criteria except for the “Investment Costs” criterion which has a quantitative scale using a linear function. In this last case the decision-maker considers that alternatives A and B are completely indifferent as long as the deviation between $f(A)$ and $f(B)$ does not exceed an established indifference threshold (the largest deviation which is considered negligible by the decision-maker)

¹ Impact Scale: 1 – very low; 2 – low; 3 – moderate; 4 – high; 5 – very high

Multi-criteria decision analysis, based on the outranking method, was used in order to provide an approach to select a robust and flexible alternative. The PROMETHEE method was used to evaluate the alternatives. PROMETHEE uses the outranking principle to rank options where, as stated by its authors, it is possible to introduce arbitrary numbers for the weights, giving the relative importance of the criteria according to the problem statement. As described by Brans and Mareschal (2005), the preference structure of PROMETHEE is based on pairwise comparisons, where the deviation between the evaluations of the alternatives for a criterion is considered.

In this study, the judgment of alternatives was based on the complete ranking, where the net outranking flow (Φ) was considered, $\Phi = \Phi^+ - \Phi^-$. The net outranking flow is the balance between the positive and the negative outranking flows. The positive outranking flow, Φ^+ , expresses how an alternative outranks all others, while the negative outranking flow, Φ^- , expresses how an alternative is outranked by all others. The net flow is built on clear and simple preference information and relies on comparative statements (Brans and Mareschal 2005).

This proposed MCA approach may serve as an example of how this analytical and decision-making process can be used for the selection of suitable alternatives for solving the drinking water problem facing the city of Cali.

Results and discussion

Impacts of Cauca River water quality on Puerto Mallarino WTP

There are two main reasons for the deterioration of water quality at the Puerto Mallarino WTP intake (Universidad del Valle and UNESCO-IHE 2008): diffuse and point sources. Diffuse sources are mainly due to the deforestation upstream, cause higher levels of erosion leading to higher turbidity during heavy rainfall events, which is a general problem for the river basin. Point sources originate for example from the South Canal (see Figure 1) and the Navarro disposal site, which discharge raw sewage and other waste materials into the river and is only 11 km upstream of the Puerto Mallarino WTP.

Operation in 1985 of the upstream Salvajina Dam also had a significant impact on the river water quality. This dam was constructed to control floods, dilute contaminants in the water and for hydro-power generation. Because of its operation, the hydraulic characteristics in the river were modified (Ramírez et al. 2010), leading to higher concentrations of suspended solids (EMCALI 1987, cited by Pérez-Vidal et al. 2012).

The Cauca River contains extremely high turbidity values (up to 10,000 NTU) according to EMCALI (personal communication, August 21, 2015) during the winter months. Contamination events decrease the dissolved oxygen (DO) to levels below 2.5 mg/L, which can indicate a serious risk to human health due to the uncertainty of the types of pollutant substances carried by the river. Water containing high suspended solids concentrations and water with low DO levels cannot be treated with the current treatment system at Puerto Mallarino WTP, resulting in the closure of the treatment plant during these concentrations. Closures leave a large proportion of the population of the city at risk of having no water during these times, with only the 80,000 m³ emergency reservoir (up to 4-hours supply capacity) available at Puerto Mallarino to bridge these periods.

Turbidity

High turbidity events in the Cauca River lead to the WTP's intake shutdowns, if over a certain threshold (2,500 NTU). An analysis of the raw water intake turbidity data at Puerto Mallarino has yielded the following information related to when turbidity peaks occur, how long they last, and how they are distributed.

High turbidity peaks generally occur during the rainy season when river flows are highest. Figure 3 illustrates the annual variations in turbidity for year 2009. Turbidity peaks occur on only a few occasions each year, and they last for periods as long as 10 hours. For most of the year, turbidity values do not fluctuate greatly and 95% of the time they remain below 568 NTU. The average annual turbidity is less than 190 NTU.

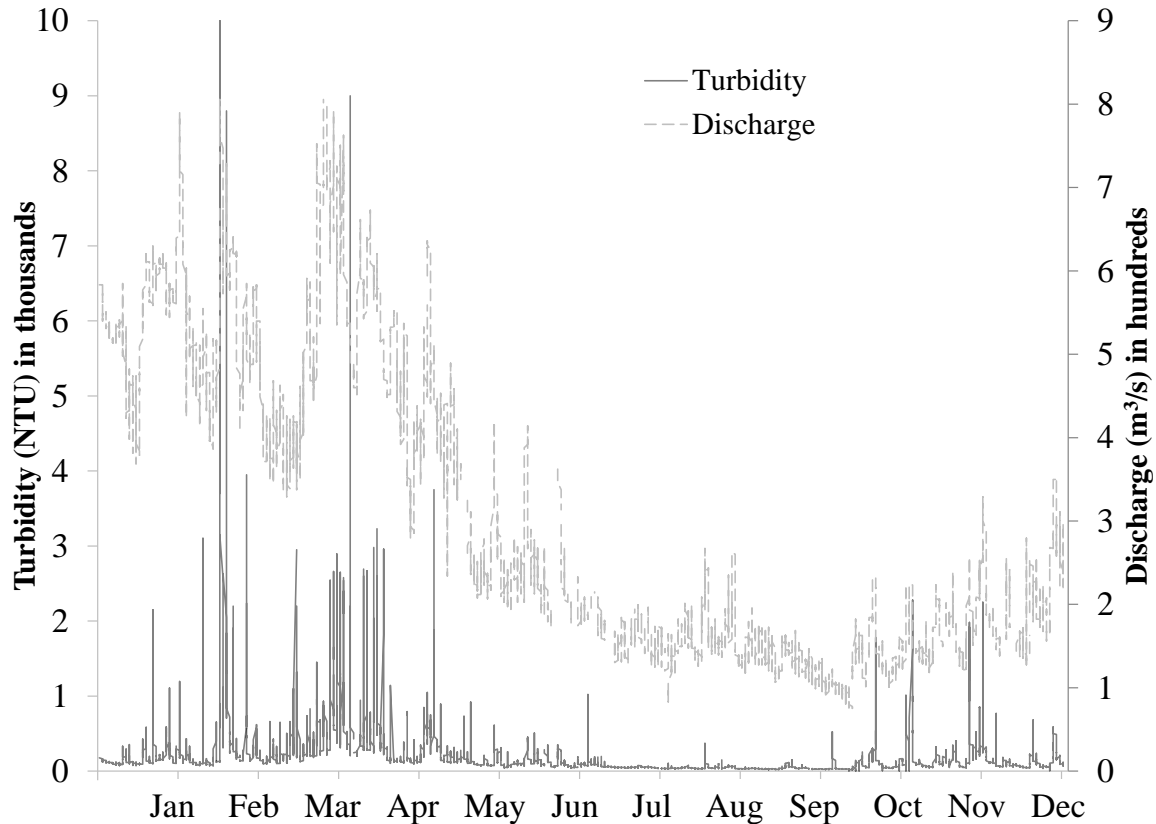


Figure 3. Annual variation of turbidity of Cauca River for year 2009

Dissolved oxygen

DO concentrations in the vicinity of Puerto Mallarino typically drop after heavy rainfalls with the increase of organic waste concentrations (CVC and Universidad del Valle 2004). The resulting low DO concentrations also lead to WTP intake shutdowns, as it is an indicator of high pollution peaks from mainly domestic, as well as industrial, wastewater. Table 3 outlines how often and for how long breaches of the critical 2.5 mg/L DO threshold occurred from 2008-2014.

Table 3. Univariate analysis of DO (2008-2014)

Year	Average DO (mg/L)	Minimum DO (mg/L)	DO events below threshold	Maximum duration of event (h)
2008	6.13	0.68	18	2
2009	5.37	0.07	20	5
2010	5.86	0.30	22	3
2011	6.44	0.08	19	2
2012	5.26	0.03	36	6
2013	5.43	0.04	41	5
2014	5.81	0.01	26	2
Overall	5.76	0.03	182	6

The 80,000 m³ reservoir can only handle events of poor raw water quality if their duration does not exceed four hours. Figure 4 shows the shutdown events that occurred between 2000 and 2014 because of turbidity and contamination events, and the effect of the 80,000 m³ reservoir in the attenuation of those events since its implementation in 2009 (EMCALI, personal communication, August 21, 2015). Low DO concentration events caused intake shutdowns at Puerto Mallarino more frequently than high turbidity peaks; however, in recent years turbidity events have become more frequent and therefore increasingly significant.

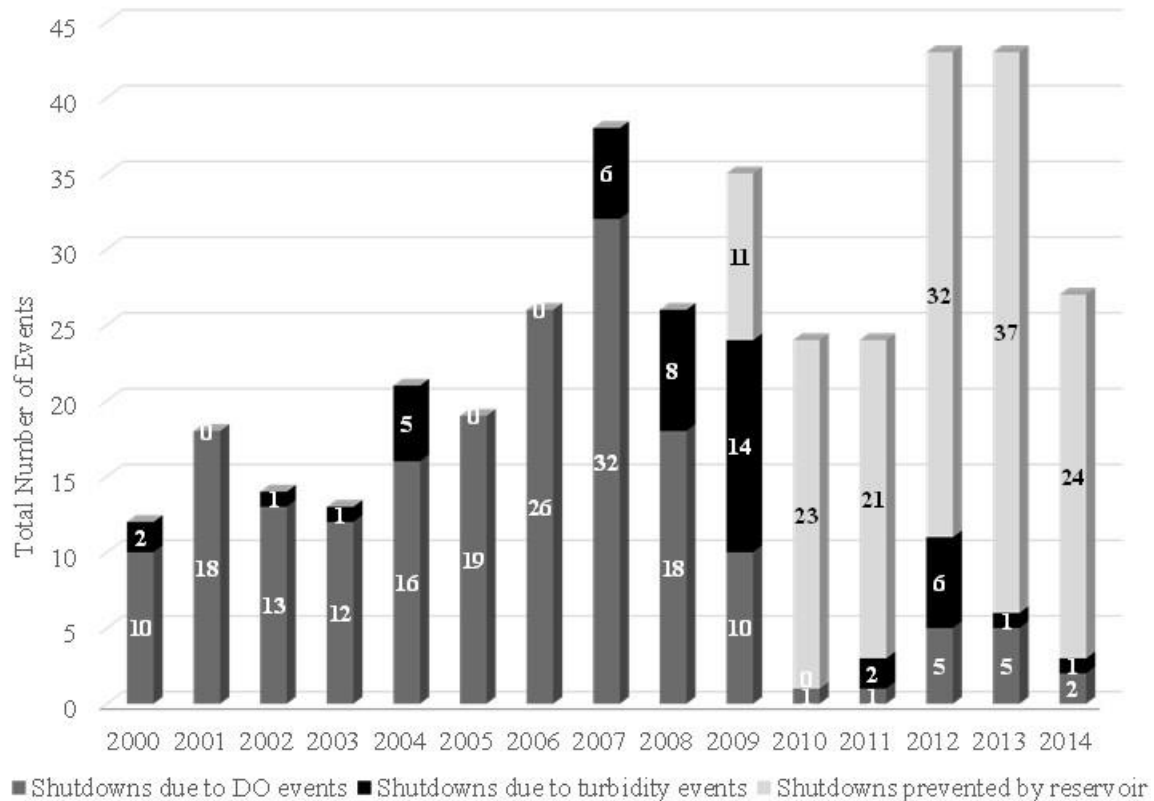


Figure 4. WTP shutdown events at Puerto Mallarino WTP (2000-2014)

Alternatives considered for resolving Cali's drinking water supply

EMCALI and CVC have been studying various alternatives at a pre-feasibility and feasibility level in order to improve the city's water supply and thereby eliminating the shutdown incidences and guaranteeing a viable water supply in the present context of increasing demand. The water sources and technologies studied are listed below, in which the alternatives considered for the analysis are denoted with the prefix "A":

Using surface water sources from the south of the region

The most recent studies were conducted by CVC between 1997 and 1999. They suggested the construction of a WTP at a Pance location which could treat water transferred from basins such as Pance, Cali or Timba through the construction of dams

(see Figure 5). The Timba basin option (Alternative 1, A1) is considered the most promising option in terms of water quantity.

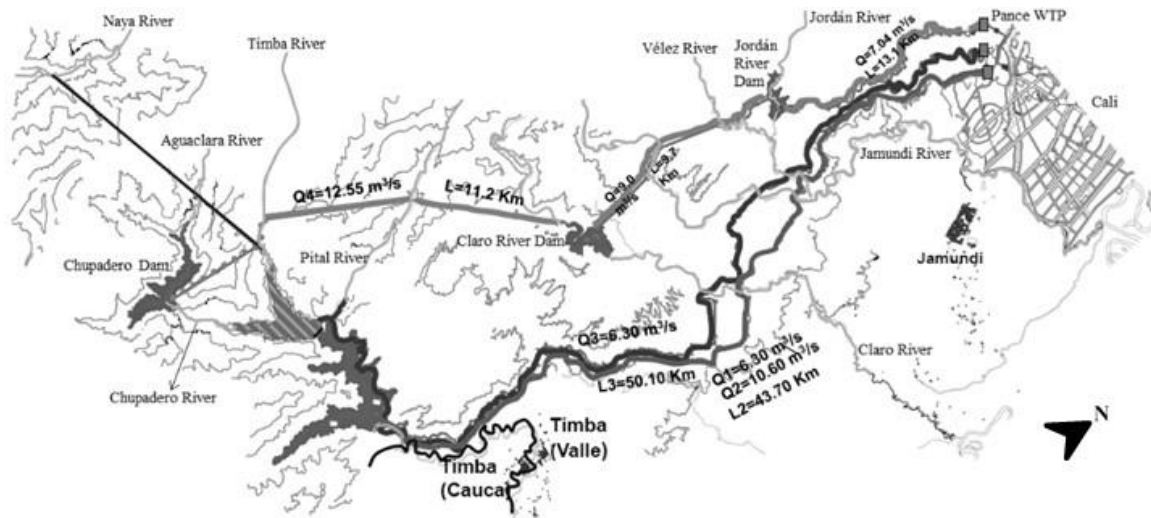


Figure 5. Scheme of alternatives at the south of the region

Source: Adapted from EMCALI (N.d.)

Relocating the Cauca River current intakes of Puerto Mallarino and Río Cauca WTPs further upstream

This alternative proposes to locate the water intake of Puerto Mallarino and Río Cauca WTPs at a point upstream of the current location and to transport the raw water to the Puerto Mallarino WTP where the treatment would take place. The possibility of extracting water at the following three locations has been considered: Salvajina dam, La Balsa and Paso de La Bolsa; all of them are located upstream of the current intake before the South Canal discharge and the discharges from turbid tributary rivers. Likewise, EMCALI has studied the alternative of relocating the intake to the places mentioned above and constructing a WTP in Pance (Figure 6). The Paso de La Bolsa point was excluded by EMCALI due to turbidity problems caused by the tributary rivers upstream of this point (mainly from the Palo and Desbaratado rivers). Therefore, the resulting alternatives are: Salvajina dam (Alternative 2, A2) and La Balsa (Alternative 3, A3) delivering to a WTP in Pance; and Salvajina dam (Alternative 4, A4); and La Balsa (Alternative 5, A5) delivering to the existing WTP in Puerto Mallarino.



Figure 6. Scheme of relocation studies at Cauca River

Source: Adapted from EMCALI (N.d.)

Using surface water sources from the Cali River basin and Pacific region

The Pichindé River, among others, has been studied to determine whether its capacity is sufficient to supply the Río Cali WTP so as to reduce dependency on the Cauca River. Between 1998 and 1999, an advanced pre-feasibility level study was conducted to determine the possibility of constructing a regulation dam in the Cali River to transfer water to the La Reforma WTP. In 2009, EMCALI evaluated the technical, financial, economical, social and environmental feasibility of constructing a regulation dam in the Cali River (EMCALI 2009). The study, at feasibility level, was carried out analyzing the availability of water with and without transferring water from the Grande River (Figure 7). Therefore, two alternatives emerge from the Cali River basin and the Pacific region: Cali River dam in conjunction with the water transference from the Pichindé River (Alternative 6, A6); and Cali River dam with Pichindé River in conjunction with the water transfer from the Grande River (Alternative 7, A7).

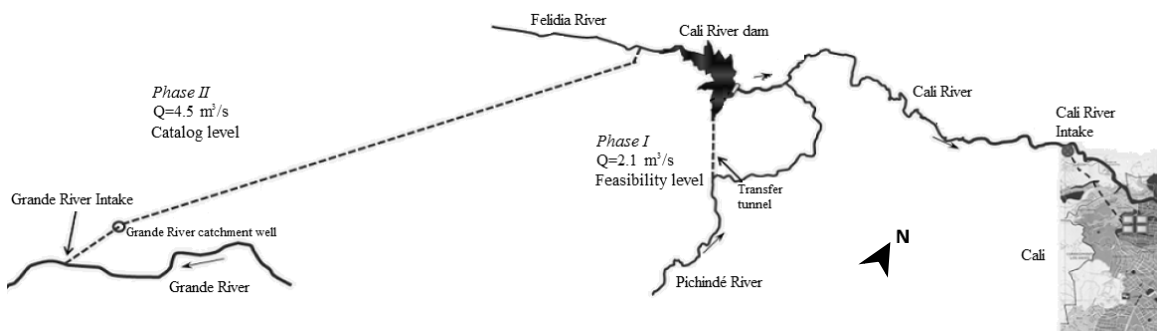


Figure 7. Scheme of advanced studies at Cali River basin and Pacific region

Source: Adapted from EMCALI (N.d.)

Using deep wells (reinstating deep wells at Aguablanca District - constructing new deep wells up to “El Hormiguero” village)

The rapid development of the District of Aguablanca in the early 90s led to the construction of four deep wells with a total capacity of 600 L/s as a supply option in this area (Figure 1). During the period between May 1992 and February 1993, the national energy crisis required that the wells be used for a few hours a day, leading to intermittent service. Therefore, the population began to store water, which led to the oxidation of iron and manganese commonly present in the groundwater, and caused a yellowish color in the water that caused displeasure and rejection among the consumers. This resulted in the suspension of the use of those deep wells for their water supply (PDA 2008). EMCALI, in 2012, publicly requested the construction of a groundwater treatment system for the removal of iron, manganese, low DO, microorganisms, methane and hydrogen sulfide in order to reinstate the aforementioned wells (Alternative 8, A8) (EMCALI 2012). A plan has been proposed to supply the extracted and treated water to the Low network. In addition, the construction of 14 more deep wells has been considered to increase water production to 2.5 m³/s (Alternative 9, A9). The wells would be constructed from the location of the current wells up to “El Hormiguero,” a community located at approximately 7 km upstream of the South Canal discharge.

Enlarging the storage capacity of the clarified water reservoir

Currently, EMCALI is enlarging the water storage capacity of the reservoir by constructing an additional 100,000 m³ reservoir (Alternative 10, A10) to increase the bridging period during critical events in the Cauca River. This decision requires an analysis of its impact on water quality, hydraulic performance and water temperature behavior on the current Puerto Mallarino WTP. This last parameter played an important role in the operational aspects since it could generate a mass inversion in water, altering the functioning of the sludge blanket and solid contact reactors of the WTP.

Using indirect abstraction from the Cauca River by riverbank filtration as a pre-treatment stage

Since 2009, riverbank filtration (RBF) (Alternative 11, A11) has been considered an alternative to resolving the water supply problems in the city of Cali, which implies process changes to the existing water treatment scheme in order to help with the variable influent loading conditions. Production wells should extract the water some distance from the water body. As the surface water travels through the sediments, it is expected that many contaminants are being removed (Schubert 2003). RBF has been used in Europe for more than 100 years (Tufenkji et al. 2002; Schubert 2002). In the United States, RBF has been used for over half a century (Ray et al. 2002). Other countries that are implementing RBF for drinking water supply are India, China, and South Korea (Sandhu et al. 2011; Ray 2008).

Analysis of alternatives

Currently, the construction of the 100,000 m³ reservoir and reinstatement of the Aguablanca wells are under execution. Therefore, for the alternatives that involve the use of the reservoir and/or the Aguablanca wells, the investment costs of these facilities were

included. In addition, O&M and sludge treatment and disposal costs were considered in the analysis. A few of the alternatives described in this study comply with the water demanded by the city (in terms of water quantity). Only three alternatives can offer the total flow of demanded water:

(A1) Timba basin;

(A2) Salvajina dam delivering water to a WTP to be constructed in Pance; and,

(A3) La Balsa delivering water to a WTP to be constructed in Pance.

In addition, a smart combination of specific alternatives can also comply with the water demand. Five combinations of alternatives – so-called combos – were defined for the remaining alternatives:

(C1): A7 + A8 + A10;

(C2): A6 + A8 + A11;

(C3): A8 + A9 + A11;

(C4): A4 + A6 + A8 + A9; and

(C5): A5 + A6 + A8 + A9

In Table 4 the evaluation results are shown. The higher the net outranking flow (Φ), the better the alternative (Brans and Mareschal 1994). The table shows that combo C3 seems to be the most adequate solution to solve the drinking water supply for Cali with a Φ of 0.55. This combo is followed by combo C2, which obtained a Φ of 0.34, which represents a good option for the city. Salvajina dam and La Balsa (A2 and A3) are also good options, giving a 0.05 and 0.01 Φ , respectively. However, these alternatives imply an important modification would need to be undertaken in the current distribution network. In addition, extracting water from La Balsa point would require pumping raw water up approximately 40 m to the WTP, and then it would be distributed by gravity. These restrictions are represented in the low Φ values obtained.

The remaining alternatives/combo obtained a negative Φ , indicating a low viability of the alternatives/combo to solve the drinking water problems in Cali. The combos C1, C4 and C5 (obtained the lower Φ values (-0.1, -0.43 and -0.40, respectively). These combos would necessitate the construction of multiple dams. The alternatives that involve the construction of dams are not well perceived by the communities and would require much time to obtain environmental and construction licenses, thereby decreasing their timely potential as a source for drinking water. This is observed in the high Φ^+ values obtained by these alternatives, and therefore in the low values observed for Φ (Table 4). In the case of the Timba basin option (alternative 1), the acquisition of large areas of land and negotiations for large pipeline trajectories until the new WTP is built would be required. The options linked to the 100,000 m³ reservoir may be susceptible to drought-flood-contamination events.

Table 4. Analysis of alternatives using PROMETHEE method based on complete ranking

Rank	MCA including all criteria			MCA excluding legal and social criteria				
	Alternative /Combo	Φ	Φ^+	Φ^-	Alternative /Combo	Φ	Φ^+	Φ^-
1	C3	0.5464	0.5886	0.0422	C3	0.6726	0.7429	0.0703
2	C2	0.3354	0.4801	0.1447	C2	0.3209	0.5621	0.2412

3	A2	0.0530	0.2840	0.2310	A1	0.1008	0.3758	0.2750
4	A3	0.0141	0.2642	0.2501	C5	-0.1403	0.2535	0.3938
5	A1	-0.0253	0.2826	0.3079	A2	-0.1497	0.2353	0.3850
6	C1	-0.0988	0.2113	0.3101	C4	-0.1868	0.2262	0.4130
7	C5	-0.3985	0.1521	0.5506	A3	-0.2146	0.2023	0.4169
8	C4	-0.4264	0.1357	0.5621	C1	-0.4028	0.1141	0.5169

By not considering legal aspects and social acceptance criteria in the assessment, the following results can be highlighted: RBF with deep wells (C3) achieved a 0.67Φ , with a $0.74 \Phi^+$ value, and the Cali River basin with RBF (C2) achieved a 0.34Φ , with a $0.57 \Phi^+$ value. This indicates that the use of RBF continues to be the best alternative, leaving out the social and legal aspects. A1 (Timba basin) obtained a positive Φ value (0.10), improving significantly its position (from 5th to 3rd). However, this alternative has great potential for legal and social constraints, which can impede its selection as a feasible solution.

Overall, RBF in combination with the Cali River basin (C2) or with the deep wells (C3) seem to be reliable solutions for the water supply problem. Figure 8 presents a potential RBF configuration for the city of Cali. The numbers enclosed in circles represent potential extraction well locations. This site was identified during an extensive desktop study that considered secondary information as well (i.e. land use plans, subsurface contamination, river morphology, distance to river course, distance to WTP and interaction with other infrastructures). The extraction capacity, constructability (how easy will the RBF configuration be to construct?), operational ease and maintainability, costs (consideration of likely construction costs and on-going maintenance costs), and the potential lowering of groundwater table were evaluated.



Figure 8. Scheme of potential locations to study RBF near the Puerto Mallarino WTP

The desktop study considered factors such as potential production capacity, potential water quality improvements, costs, environmental impacts, O&M considerations and regulatory considerations. Both the quality and quantity aspects of implementing RBF in Cali showed promising results, but it must be studied further to determine its technical feasibility. In addition, the high concentration of sediments transported by the Cauca River could lead to an important reduction of its water yield.

Conclusions

The drinking water supply system of Cali is vulnerable due to its dependence on WTPs abstracting water from the Cauca River. Therefore, alternatives are being considered and evaluated with a multi-criteria analysis (MCA). RBF in combination with the deep wells and RBF with the Cali River basin options seem to be ideal alternatives in order to guarantee safe drinking water in the amounts demanded by the city, while also having a lower environmental impact during construction and operation.

MCA has been shown to be a suitable tool in the analysis of problems where political, social and stakeholders' interests are involved. However, it is subjected to individual preferences that can alter the results depending on what the developers favor. Selection of a broad range of criteria, in addition to the weighting process, plays an essential role, since it allows compensating subjective decisions and guidelines proposed by institutions. The participation of experts and stakeholders in this process provided a comprehensive conceptualization of the problem, facilitating the construction of an integrated multiple-criteria framework to assess the selection of the alternatives. This analysis provided transparency for the decision-making process and engaged stakeholders in the search for solutions that best suit the addressed needs.

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