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Corrosion control using hydroxide and bicarbonate alkalising agents in water drinking processes

P. Torres-Lozada, K. A. Bueno-Zabala, L. G. Delgado-Cabrera, L. E. Barba-Ho, and C. H. Cruz-Vélez

Universidad del Valle, Cali, Colombia

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Correspondence to: P. Torres-Lozada (patricia.torres@correounivalle.edu.co.)

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Abstract

The water supply industry is faced with three phenomena of great importance: the aggressiveness, corrosion, and incrustation of water distribution systems (WDS), which are primarily due to the low alkalinity of water sources and the addition of chemicals used in water treatment processes, which require pH adjustments during the last stage of the treatment process before going into the WDS. This article presents the results of using $Ca(OH)_2$ and NaOH with doses between 2 and 20 mg L^{-1} and $NaHCO_3$ and Na_2CO_3 between 10 and 250 mg L^{-1} to adjust the pH of water treated from the Cauca River, which is located in Cali, Colombia, using stabilisation indices normally used in water treatment plants for pH monitoring processes and to better predict the behaviour of water in the WDS. The results indicate that for the case of the surface water source studied, which exhibits low alkalinity levels, the evaluated alkalising agents, with the exception of $NaHCO_3$, can create conditions that lead to the precipitation of a protective calcium carbonate film. Because the pH values that guarantee an adequate pH adjustment are higher (8.7–9.0) than those specified by the Colombian water code and because other international rules indicate that these values do not compromise the health of consumers, it is advisable to review and adjust the code in this respect.

1 Introduction

When treating water to make it potable, the processes of coagulation and disinfection reduce alkalinity and pH (WHO, 2011), which makes it necessary to equilibrate the chemical balance of water at the end of the treatment to reduce its corrosive capacity and ensure that no encrustations are formed, which can cause reduction in the flow section (Barid, 2004; Casey, 2009). These situations have economic, hydraulic, aesthetic, and public health repercussions, which include water leaks, increased pumping costs, and deterioration of water quality in WDSs (Volk et al., 2000; Gray, 2008).

For the pH adjustment process, there are several alkalising agents in use, which include strong base neutralisation (hydrated lime ($Ca(OH)_2$) and sodium hydroxide (NaOH)) and neutralisation with an alkaline carbonate (sodium carbonate and bicarbonate (Na_2CO_3; $NaHCO_3$) and calcium carbonate ($CaCO_3$)). Furtado et al. (2011) found that $Ca(OH)_2$ and $NaHCO_3$ are effective compounds to increase the alkalinity, whereas Na_2CO_3, although it raises the pH, is not as effective in that regard.

One technique to evaluate the pH adjustment process is to use stabilisation indices, where the most widely used are those that indicate water saturation, such as the $CaCO_3$ Langelier saturation index (LSI), McCauley's driving force index (DFI), $CaCO_3$ precipitation potential (CCPP), and those that depend on the type of piping, i.e., the aggressive index (AI), Larson-Skold index (LKI) and Ryznar stability index (RSI) (Schock, 2002; Imran et al., 2005; Trujillo et al., 2008; De Moel et al., 2013). However, authors such as Varó Galváñ et al. (2004) have indicated that there is still no index available that is universally applicable, which requires analysing the treatment process using several indices to determine the appropriate conditions for each WDS.

By applying stabilisation indices, this study evaluated the influence of alkalising agents (hydrated lime, sodium hydroxide, sodium bicarbonate and sodium carbonate) on controlling corrosion in water treated from the Cauca River, which supplies a high percentage of the water for the city of Cali, Colombia.

2 Materials and methods

The study was conducted in the Puerto Mallarino water treatment plant (WTP) in the city of Cali, which treats raw water from the Cauca River. The following are the stages developed in this study: evaluate the effects of adding chemicals used in water treatment processes on the water's pH and total alkalinity and evaluate the pH adjustment using different alkalising agents.

2.1 Evaluation of the effect of adding chemicals used in water treatment processes on pH and total alkalinity

Historical daily information was gathered and processed during the year 2012, which is available from EMCALI EICE ESP, regarding the raw water turbidity from the Cauca River and its relationship and effect on the dosage of the chemical products used during water treatment processes (coagulant, adsorbent, disinfectant, and alkalising agent) and on the total alkalinity (mg $CaCO_3$ L^{-1}) and pH in the water after it has been cleared, filtered, and treated.

2.2 Evaluation of the pH adjustment with different alkalising agents

2.2.1 Comparative analysis of alkalising agents

By means of a bibliographical review, a comparative analysis was conducted on the alkalising agents with the most widespread application, such as hydrated lime, sodium hydroxide, sodium bicarbonate, sodium carbonate, and calcium carbonate. The primary characteristics of each alkalising agent were grouped into three categories: technical aspects, occupational health, and economics, leading to a selection of the alkalising agents to be evaluated at the laboratory scale with treated water from the Cauca River.

2.2.2 Laboratory-scale evaluation of alkalising agents

For the pH adjustment, hydrated lime ($Ca(OH)_2$), sodium hydroxide (NaOH), sodium bicarbonate ($NaHCO_3$), and sodium carbonate (Na_2CO_3) were evaluated using 4 % concentration solutions. According to Bueno-Zabala et al. (2014), to generate oversaturation conditions that allow for precipitation of the calcium carbonate film for the treated water from the Cauca River, it is necessary for the pH at the end of the process to exceed the saturation pH (pHs), which is between 8.7–9.0. For that reason, the doses used for $Ca(OH)_2$ and NaOH were between 2 and 20 mg L^{-1}, whereas those for $NaHCO_3$ and Na_2CO_3 were between 10 and 250 mg L^{-1}.

Tests were conducted using jar test equipment in duplicates and with chlorinated water from the Puerto Mallarino WTP. The sample volume was 2 L, and the mixing was performed at 60 RPM for one minute (Colindres, 2010; Bordoloi et al., 2013). The control variables were the pH and total alkalinity.

Table 1 shows the variables monitored to measure the pH adjustment process through the stabilisation indices presented in Tables 2 and 3, which were classified in the following way: tendency towards precipitation of $CaCO_3$ (LSI, DFI, and CCPP) (Table 2) and type of piping (AI, LKI, and RSI) (Table 3). Tables 2 and 3 present the main equations, interpretation, and characteristics of each index.

3 Results and discussion

3.1 Evaluation of the effect of adding the chemicals used in water treatment processes on pH and total alkalinity

Figure 1 shows the turbidity behaviour (UNT) of the raw water and its effect on the chemical doses and total alkalinity (mg $CaCO_3$ L^{-1}) and the pH of the water after it has been cleared, filtered, and treated.

With respect to the raw water of the Cauca River, it can be seen in Fig. 1a that the turbidity exhibits high variability that is primarily associated with phenomena, such as solid suspensions (Rodríguez et al., 2010), dragging of domestic and industrial discharges, agricultural and mining runoff, and sediments (Pérez-Vidal et al., 2014). This variability has a direct effect on the dosage of chemicals (Fig. 1b), particularly for the coagulant ($p < 0.5$).

The addition of chemicals, both for coagulation and for disinfection, generates the consumption of total alkalinity (Fig. 1c) and reduces the pH (Fig. 1d), which can be particularly observed for clarified water given that before this stage, the processes of primary disinfection (chlorination) and coagulation have occurred. These values remain in the filtered water and require adjustment after disinfection; in the case of the water studied, the pH adjustment process is performed using $Ca(OH_2)$, which reached median levels between 7.0–7.3; however, although these values are within the range specified in the national water code, the values are below the pHs mentioned previously, and in the case of total alkalinity, it also does not guarantee the saturation conditions that promote the formation of a calcium carbonate film in the WDS (Varó Galváñ et al., 2004; WHO, 2011), which ratifies the need to evaluate and optimise the pH adjustment process.

3.2 Evaluation of pH adjustment with different alkalising agents

3.2.1 Comparative analysis of alkalising agents

Table 4 shows the primary characteristics of the most widely used alkalising agents during the pH adjustment process, grouped by technical, health, and economic aspects. It can be seen that strong bases ($Ca(OH_2)$ and NaOH) provide the most total alkalinity directly from OH^- ions; however, they do not contribute any buffer capacity to the system. For the case of bicarbonates and carbonates ($NaHCO_3$, Na_2CO_3, $CaCO_3$), despite contributing a lesser total alkalinity due to being in the form of salts, they provide a buffer capacity by way of HCO_3^- and CO_3^{2-} ions (Furtado et al., 2011).

With respect to $Ca(OH)_2$, in the majority of cases, it is better to produce it based on CaO as the raw material because CaO contains a higher percentage of active ingredient than slaked lime; however, the process of slacking requires more time on part of the operators and consumes clean water (Lozano, 2006; Procecal, 2009). In Colombia, CaO is easy to acquire and is inexpensive; however, due to its low solubility, the dosage requires constant maintenance, inspection chambers, a possible increase in final turbidity, and encrustations after long stretches, where the preparation point of the mixture is far from its application (Withers, 2005; Labiod and Ghizellaoui, 2012). In terms of occupational health, CaO is classified by the NFPA 6704 (National Fire Protection Association) as very dangerous because it liberates heat when reacting with water, which can lead to combustion of materials in contact or close by, such as paper, fabric, cardboard, etc. (Calidra, 2007).

NaOH is easy to handle because its high solubility achieves good mixtures, avoids encrustations or increased turbidity in the final water, and is easy to acquire nationally. In addition, it has a high percentage of the active ingredient as a raw material, which is expensive (Sallanko et al., 2013). In terms of occupational health, NFPA 704 classifies it as very dangerous because it is highly corrosive and may cause severe burns, which requires special care for storage, specifically the need to use high-density polyethylene materials and precautions in electric power transmission lines due to the possibility of generating flammable hydrogen (GQ, 2006; Kim et al., 2008; Vargas et al., 2009).

$NaHCO_3$ is easy to handle given that it is more soluble at temperatures greater than 28 °C, where it behaves as sodium carbonate; it is widely available nationally, has a high percentage of active content, and is inexpensive as a raw material (Berrenechea, 2004; GQ, 2006; Ebbing and Gammon, 2010). Although it is harmless in terms of occupational health, even when present at high levels (Takasaki and Yamada, 2007), it may be necessary to mix it with $Ca(OH)_2$ or NaOH to adjust the pH in the case when a $pH > 8$ is required because it is a product that gradually changes the water's equilibrium (Kim et al., 2008; Casey, 2009). As a result, its application is recommended in small-scale plants or when $Ca(OH)_2$ creates problems (GQ, 2006; Casey, 2009).

Na_2CO_3, as $NaHCO_3$, is easy to handle and must be used with another alkalising agent primarily because of its high cost in the market and the addition of unwanted cations in the water (Manharawy and Hafez, 2002; Colindres, 2010). Na_2CO_3 has a high content of active ingredient and its availability is limited. In addition to being imported, it is a nationally controlled substance (CNE, 1987; Di Bernanrdo and Sabogal, 2008; Birhnack et al., 2011). The NFPA 704 classifies it as dangerous, which requires specialised materials for handling (Hilleboe, 2000; Kim et al., 2008).

$CaCO_3$ is primarily used in countries such as Mexico, Ecuador, Argentina, and Brazil, which incurs additional costs from importing. This product has a high active content,

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and the NFPA 704 classifies it as slightly dangerous; however, being less soluble than $Ca(OH)_2$, it requires previous acidification in water with CO_2, which must remain for at least 15 min in a reactor, and another alkalising agent must be added to reach adequate pH values (Birhnack et al., 2011; Lehmann et al., 2013).

Although the analysed products have the potential of being used in pH stabilisation processes, their selection depends on the different factors mentioned previously and on aspects such as the characteristics of the raw water, type of treatment processes previously used, availability at the site, etc. For this reason, $CaCO_3$ was not evaluated in this study, given its limitations such as requiring added CO_2 and importation of the product.

3.2.2 Laboratory-scale evaluation of the alkalising agents

Figure 2 shows the behaviour of the alkalising agents evaluated with respect to total alkalinity and final pH of the treated water from the Cauca River.

According to Fig. 2, strong bases increase total alkalinity values and pH with low doses, whereas salts require higher doses, which agrees with the results reported by De Sousa et al. (2010). However, strong bases do not provide the minimum alkalinity required for maintaining a buffer capacity in the WDS (approximately $40\,mg\,CaCO_3\,L^{-1}$) due to their chemical reactions (Birnhack et al., 2011).

In terms of final pH, the only alkalising agent that did not achieve the minimum pH ($pH = 8.7–9.0$) to create the tendency of precipitating a calcium carbonate film was $NaHCO_3$ because the maximum pH that was reached was 8.0. $NaCO_3$ achieved the required values for both total alkalinity and minimum pH, though requires doses larger than $130\,mg\,L^{-1}$, which could lead to problems in dosage and storage depending on the volume of water to be stabilised (Dongchan et al., 2008).

Figure 3 shows the behaviour of the alkalising agents evaluated through the indices that exhibit the tendency to precipitate calcium carbonate (LSI, DFI, and CCPP) and those that are used depending on the type of piping (AI, LKI, and RSI). It can be seen that all alkalising agents, except for $NaHCO_3$, exhibit conditions that favour the tendency to precipitate calcium carbonate in the WDS given that the evaluated doses show results of oversaturated water and obtained pH values that exceeded the pHs. $NaHCO_3$ does not achieve this because the final pH oscillates between 7–8.3 because the bicarbonate ions generally remain in that range within the carbonate system (Ebbing and Gammon, 2010; Birnhack et al., 2011).

With respect to the indices that apply to specific types of piping materials in the WDS, such as AI for asbestos cement piping, i.e., AC (31.9 % of the city of Cali's WDSs is made of AC and is also the oldest), it can be seen that all the alkalising agents, with the exception of $NaHCO_3$, allow for obtaining water with non-aggressive tendencies due primarily to the fact that the pH values of the water exceed the pHs.

For the LKI index applied to metallic piping (11.5 % of the city of Cali's WDSs), only $NaHCO_3$ and Na_2CO_3 resulted in a slight to small potential for corrosion with doses greater than 200 $mg\,L^{-1}$ because they generate a total alkalinity greater than 50 $mg\,CaCO_3\,L^{-1}$ (Agatemor and Okolo, 2008; Trujillo et al., 2008). For the RSI applied for steel piping (1.2 % of the city of Cali's WDSs), it was found that no alkalising agent would generate encrustation conditions, and although Na_2CO_3 exhibits conditions close to equilibrium with doses of 250 $mg\,L^{-1}$, it would exceed Resolution 2115/2007 in terms of total alkalinity and pH.

Regarding the use of products containing sodium (Na^+), it is advisable to control their concentration in water. The WHO (2011) recommends a concentration of less than 200 $mg\,L^{-1}$ because it may generate rejection by users due to causing flavour problems of the water; the concentrations obtained in this study did not exceed this value (3.0–92.6 $mg\,Na^+\,L^{-1}$).

Table 5 shows certain international guidelines and rules in addition to the Colombian code for the operation conditions in terms of doses, pH, and total alkalinity in accordance with the optimum results of pH stabilisation indices, LSI, DFI, CCPP, and AI, for the alkalising agents evaluated, with the exception of $NaHCO_3$ because it was the only one that did not obtain adequate pH adjustment conditions.

The results in Table 5 show that in terms of application dose, $Ca(OH)_2$ would require the least amount of raw material to obtain optimum results during the pH adjustment process, followed by NaOH and Na_2CO_3; however, the latter requires doses greater than 130 $mg\,L^{-1}$, which could lead to dosage problems (Dongchan et al., 2008). To select an alkalising agent, one must take into account each of the agents' limitations because in general, $Ca(OH)_2$ exhibits low solubility problems in water, NaOH requires more complex storage conditions, and Na_2CO_3 is a controlled substance in Colombia (Vargas et al., 2009; Labiod and Ghizellaoui, 2012; Sallanko et al., 2013).

As the main variable in the stabilisation process, pH must be controlled to reduce corrosion in the WDS to a bare minimum, which avoids possible water contamination due to metal dissolution and adverse effects in appearance and flavour (Tam and Elefsiniotis, 2009; Wilczak et al., 2010; WHO, 2011).

One aspect of these results that should be highlighted is that the current Colombian code does not allow for adequate conditions to be obtained to remove the calcium carbonate film in Cali's WDSs, which is primarily due to the pH limitation because getting good results requires the pH to exceed the pHs, which is between 8.7–9.0, a range that is at the upper bound of Resolution 2115/2007. However, the fact that other countries, such as Brazil, the European Union, and the United Kingdom, allow maximum values of $pH > 9.0$ to reduce the effect of corrosion in WDSs (Hamdy et al., 2011; Rout et al., 2014) leads us to recommend a review of this rule.

The value of alkalinity at the end of the stabilisation process for treated water from the Cauca River should be at a minimum range, between 27.3–36.7 $mg\,CaCO_3\,L^{-1}$ (Bueno-Zabala et al., 2014), which is in accordance with recommendations in the literature (between 40 and 80 $mg\,CaCO_3\,L^{-1}$) to precipitate a calcium carbonate film in the WDS (Berghult et al., 1999; Imran et al., 2005). Although $Ca(OH)_2$ and NaOH rapidly increase pH, they do not achieve adequate alkalinity results that provide a greater capacity to neutralise acids and avoid pH reductions in the WDS; in contrast, Na_2CO_3 reaches the desired total alkalinity values but requires greater doses due primarily to the contribution of alkalinity per mg L^{-1} of the product added (0.94 mg $CaCO_3$ L^{-1}) (Birnhack et al., 2011; Crittenden et al., 2012).

The results make it advisable to continue evaluating the pH adjustment process to create combinations of alkalising agents that provide adequate values of total alkalinity and pH and to evaluate other alternatives for process control and optimisation, such as increasing alkalinity from the supply source; using other types of coagulant; and mixing alkalising agents or strong bases with the addition of CO_2 to increase acidity through the formation of carbonic acid, which subsequently reduces the pH values that exceed the national code (Withers, 2005; Hart, 2008; Birnhack et al., 2011).

4 Conclusions and recommendations

Alkalising agents, such as hydrated lime, sodium hydroxide, and sodium carbonate, create water conditions that have a tendency to precipitate a calcium carbonate film in the WDS of the city of Cali; however, their selection depends on the characteristics of the raw water and on technical, economic, and occupational health aspects.

The application dosage recommended for generating water conditions with the tendency to precipitate a calcium carbonate film and non-aggressive conditions for asbestos cement piping in the WDS of the city of Santiago de Cali, according to the LSI, DFI, CCPP, and AI indices, are between 6 and 10 mg L^{-1} for hydrated lime and sodium hydroxide and between 130 and 200 mg L^{-1} for sodium carbonate; however, such high doses could lead to dosage problems.

Application doses greater than 200 mg L^{-1} for sodium bicarbonate and carbonate generate results with a slight to small potential for corrosion in metallic piping according to the LKI index. For steel piping, none of the evaluated alkalising agents with maximum doses of 250 mg L^{-1} generates encrustation conditions according to the RSI index.

Application of the stabilisation indices shows their great potential for monitoring the pH adjustment process and better predicting the behaviour of water in WDSs; however, because there is no index that is universally applicable and others depend on the type of piping material of the WDS, it is necessary to use at least one index that provides information regarding the tendency for $CaCO_3$ precipitation (LSI or DFI) along with calculating the CCPP and another index that reflects the needs of the WDS according to the type of piping material.

The required pH values that guarantee adequate pH adjustment are higher than those indicated in the Colombian code for drinkable water because post-treatment pH should be equal or higher than the saturation pH ($pH = 8.7–9.0$). Bearing in mind that other international codes are more flexible in that regard and do not compromise the health of consumers, we consider it necessary to review and adjust the code on this aspect.

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Table 1. Test variables.

Variable	Units	Reference technique[a]
pH	–	4500-H^+ B
Total alkalinity	mg $CaCO_3$ L^{-1}	2320-B
Total hardness	mg $CaCO_3$ L^{-1}	2340 C
Calcic hardness	mg $CaCO_3$ L^{-1}	2340 C
Calcium	mg Ca^{2+} L^{-1}	3500-Ca D
Sodium	mg Na^+ L^{-1}	3500-Na B
Temperature	°C	2550-B
Turbidity	UNT	2130-B
Chlorides	mg Cl^- L^{-1}	4500-Cl^- B
Sulphates	mg SO_4^{2-} L^{-1}	4500-SO_4^{2-} E

[a] APHA et al. (2005).

Table 2. Indices with the greatest applicability in controlling the pH stabilisation process: tendency towards precipitation $CaCO_3$.

Index	Equation
Langelier Saturation Index (LSI)	$\mathrm{LSI} = \mathrm{pH} - \mathrm{pH_s}$ (1) Where: pH at the site; $\mathrm{pH_s}$: saturation pH Interpretation: $\mathrm{LSI} > 0$, oversaturated; $\mathrm{LSI} = 0$, saturated; $\mathrm{LSI} < 0$, unsaturated Characteristic: Indicator for conditions of precipitation of $CaCO_3$
McCauley Driving force Index (DFI)	$\mathrm{DFI} = \dfrac{[\mathrm{Ca}^{2+}]\cdot\left[\mathrm{CO}_3^{2-}\right]}{K_s 10^{10}}$ (2) Where: $[\mathrm{Ca}^{2+}]$: Calcium in mg $CaCO_3$ L^{-1}; $\left[\mathrm{CO}_3^{2-}\right]$: Carbonate concentration; K_s: Solubility product of $CaCO_3$ Interpretation: $\mathrm{DFI} > 1$, oversaturated; $\mathrm{DFI} = 1$, saturated; $\mathrm{DFI} < 1$, unsaturated Characteristic: Measures the tendency to deposit a $CaCO_3$ film
Calcium Carbonate Precipitation Potential (CCPP)	$\mathrm{CCPP} = \mathrm{Alk_i} - \mathrm{Alk_{eq}}$ (3) Where: $\mathrm{Alk_i}$: Initial alkalinity; $\mathrm{Alk_{eq}}$: Equilibrium alkalinity Interpretation: $\mathrm{CCPP} > 0$, oversaturation and mg $CaCO_3$ L^{-1} that must be precipitated; $\mathrm{CCPP} < 0$, unsaturation and $CaCO_3$ that dissolve Characteristic: Indicates the theoretical approximate mass of $CaCO_3$ that could be precipitated in the piping

Source: Schock (2002), Varó Galváñ et al. (2004), APHA et al. (2005), Imran et al. (2005), Trujillo et al. (2008), De Sousa et al. (2010), De Moel et al. (2013), Bueno-Zabala et al. (2014).

Table 3. Indices with the greatest applicability in controlling the pH stabilisation process: type of piping.

Index	Equation
Aggressive Index (AI)	$\mathrm{AI} = \mathrm{pH} + \log(AH)$ (4) Where: pH: Hydrogen ion potential; A: Total alkalinity; H: Calcium hardness Interpretation: $\mathrm{AI} < 10$, very aggressive; $10 < \mathrm{AI} < 12$, moderately aggressive; $\mathrm{AI} > 12$, not aggressive Characteristic: Estimates the tendency of water to deteriorate the asbestos cement piping structure
Larson-Skold Index (LKI)	$\mathrm{LKI} = \frac{[\mathrm{Cl}^-] + 2\left[\mathrm{SO}_4^{2-}\right]}{[\mathrm{HCO}_3^-]}$ (5) Where: Cl^-: Chlorides ($\mathrm{mol\,L^{-1}}$); SO_4^{2-}: Sulphates ($\mathrm{mol\,L^{-1}}$); HCO_3^-: Bicarbonates ($\mathrm{mol\,L^{-1}}$) Interpretation: results represented in corrosion potential: < 0.2, does not exist; 0.2–0.4, small; 0.4–0.5, slight; 0.5–1.0, average; > 1, Strong Characteristic: Represents the corrosiveness due to chloride and sulphate ions. Applied in metallic piping and waters with medium to high alkalinity (> 50 mg $\mathrm{CaCO_3\,L^{-1}}$)
Ryznar Stability Index (RSI)	$\mathrm{RSI} = 2\mathrm{pH_s} - \mathrm{pH}$ (6) Where: pH at the site; $\mathrm{pH_s}$: saturation pH Interpretation: $\mathrm{RSI} < 6.5$, causes encrustation; $6.5 < \mathrm{RSI} > 7$, close to equilibrium; $\mathrm{RSI} > 7$, corrosive Characteristic: Determines the corrosive or encrustation character of water. Applies to steel piping and water with medium to high alkalinity (> 50 mg $\mathrm{CaCO_3\,L^{-1}}$)

Source: Schock (2002), Varó Galváñ et al. (2004), APHA et al. (2005), Imran et al. (2005), Trujillo et al. (2008), De Sousa et al. (2010), De Moel et al. (2013), Bueno-Zabala et al. (2014).

Table 4. Technical, occupational health, and economic aspects of the alkalising agents used in pH adjustment.

Characteristic		Alkalising agent				
		Hydrated lime $Ca(OH)_2$	Sodium hydroxide $NaOH$	Sodium bicarbonate $NaHCO_3$	Sodium carbonate Na_2CO_3	Calcium carbonate $CaCO_3$
Technical	Chemistry	Strong base		Salt		
	Total alkalinity contribution (as $CaCO_3$	1.35	1.25	0.60	0.94	1.00
	Buffer capacity contribution	0 equivalent	0 equivalent	1 equivalent HCO_3^-	2 equivalent CO_3^{2-}	2 equivalent CO_3^{2-}
	Storage	Simple	Specialised	Simple		
	Dosage	Complex (Lime slacking, encrustations)	Easy (Does not form insoluble salts)	Medium complexity (Mix with bases and addition of unwanted cations in the water)		Complex (Acidify with CO_2 combination with another alk.)
Occupational Health	NFPA 704 Evaluation - National Fire Protection Association (Scale 0: Minimum; 1: Slight; 2: Moderate; 3: Serious; 4: Severe)	Occupational Health				
		CaO: 3 (Very dangerous) Slaked lime: 1 (Slight danger)	3 (Very Dangerous)	0 (No risk)	2 (Dangerous)	1 (Slightly dangerous)
		Flammability				
		0 (Does not ignite)				
		Reactivity				
		0 (Stable)	1 (Unstable in case of heating)	0 (Stable)		
Economic	Easy to acquire in Colombia	Yes			Yes – Controlled in Colombia	No but it is in Mex., Ecua., Arg., Bras.
	Solubility (g prod./100 mL water) 20 °C	0.2	111	9.6	7.1–10	0.0014
	% Available active content	CaO: Min. 90 % Slaked lime: 75–84 %	99–100 %	98–100 %	98–99 %	95–99 %
	Raw material cost [a] (COP$ kg^{-1} w/o tax)	CaO: 336 Slaked lime: 475	1050	31.2	900[b]	80 (0.04U$)[b]

[a] Final cost should include raw material cost, dosage, and buffer capacity.

[b] Transportation not included.

Source: Kim et al. (2008), Colindres (2010), Ebbing and Gammon (2010), Birnhack et al. (2011), Lehmann et al. (2013).

Table 5. Operation conditions and results of pH stabilisation with different alkalising agents.

	Alkalising agents			Code	
Parameter	Hydrated lime	Sodium hydroxide	Sodium carbonate	National (Res. 2115/07)	International
Dose ($mg\,L^{-1}$)	6–8	8–10	130–200	–	–
pH (–)	8.8–9.3	9.1–9.4	8.6–9.0	6.5–9.0	6.0–9.5[a] 6.5–9.5[b] 6.5–10.0[c]
Total alkalinity ($mg\,CaCO_3\,L^{-1}$)	14–16	16–19	85–125	200	–

[a] Brazil, PORTARIA No. 518/2004.

[b] Unión European, Directive 98/83/CE.

[c] England and Wales, No. 3911/2001 (W.323)

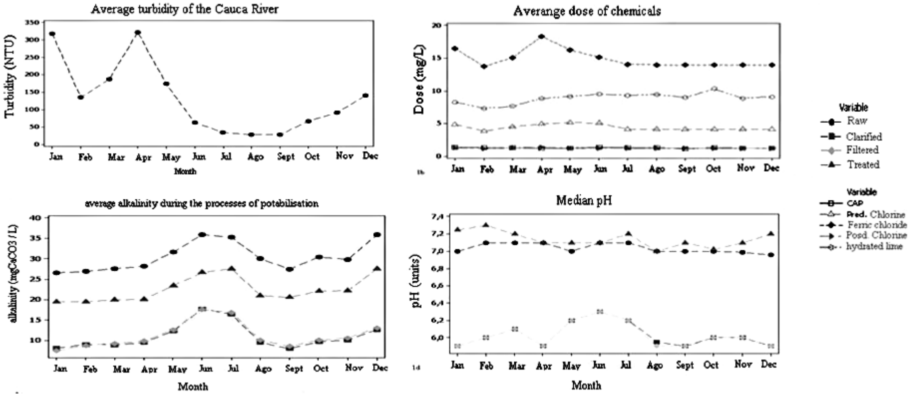

Figure 1. Turbidity behaviour of the Cauca River, chemical doses, and their effect on alkalinity and pH during the water treatment processes. Historical daily data for the year 2012.

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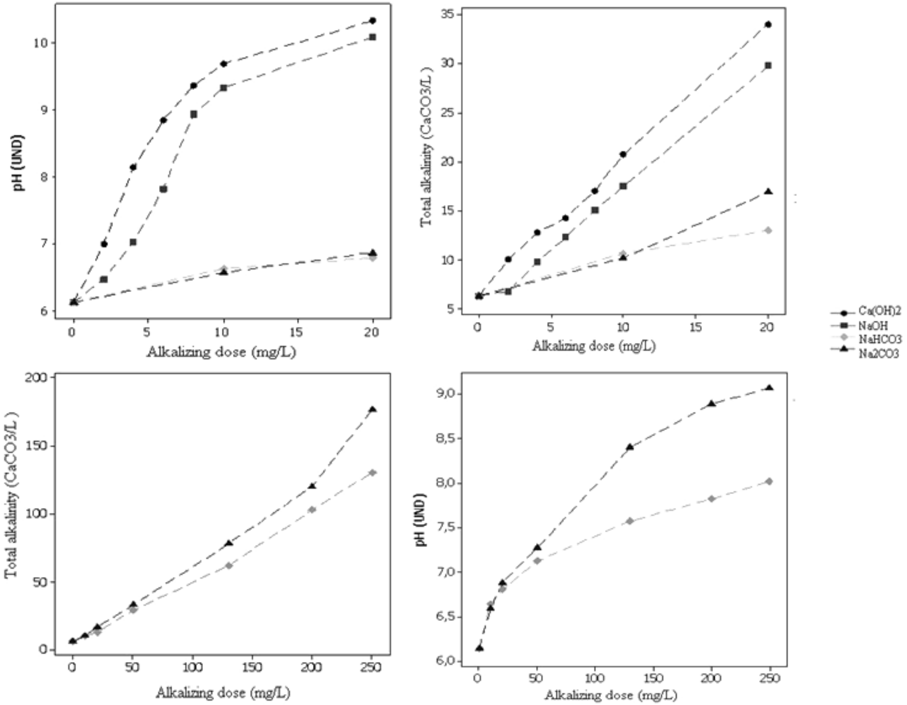

Figure 2. Effect of different alkalising agents on total alkalinity and pH for the evaluated doses.

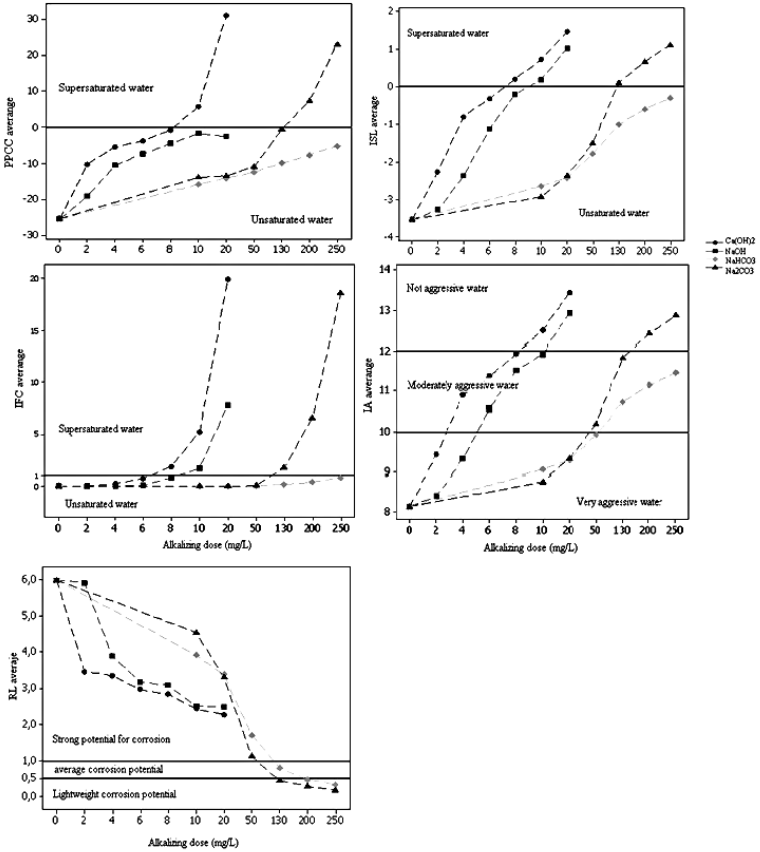

Figure 3. LSI, DFI, CCPP, AI, LKI, and RSI indices for hydrated lime, sodium hydroxide, sodium bicarbonate, and sodium carbonate.