International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 22 (2018) pp. 16093-16099
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Operational Analysis in a Drinking Water Treatment Plant using ARIMA Models

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Abstract

This paper shows an operational analysis in a Drinking Water Treatment Plant (DWTP) using ARIMA Models: 'El Dorado' (Bogota, Colombia). A comparative analysis was carried out between concentrations of water quality parameters, and Colombian legislation and guidelines established by the World Health Organization. We studied the rainfall influence in relation to changes in water quality supplied by the DWTP. A correlation analysis between water quality parameters was also carried out to identify control parameters during the DWTP operation. The results showed the effectiveness of ARIMA models for analyzing the operation in DWTP from a weekly timescale (medium-term), and not from a daily timescale (short-term). This was due to significant daily variations in the control parameters of water quality in the DWTP. The application of a weekly moving average transformation to the daily time series of water quality parameter concentrations significantly decreased the mean absolute percentage error (MAPE) in the forecasts of ARIMA models developed. ARIMA analysis suggested an influence of the water quality parameter concentrations observed in the DWTP during previous weeks (between 2 and 3 weeks). This study was probably constituted as a medium-term planning tool in relation to atypical events or contingencies observed during the DWTP operation. Finally, the findings in this study will be useful for companies or designers of drinking water treatment systems to take operational decisions within the public health framework.

Keywords: Water quality, ARIMA models, purification, time series.

INTRODUCTION

Bogota city (Colombia) is mainly supplied with drinking water through the network of the Bogota Aqueduct Company (EAB), which for the year 2010 reached a coverage of 99.9%. However, the remaining percentage of population did not have optimal service and was susceptible to water quality-related diseases. It was evidenced between the years 2008-2010 the cases occurrence of A-type acute hepatitis, enteritis, and acute amebic dysentery; counting a total of 13058 cases in the city and specifically 9011 cases in the localities of Usaquen and Chapinero (SDA, 2011).

In the Colombian context, Resolution 2115 (2007) established a water quality risk index for human consumption (IRCA) as a monitoring and control instrument in relation to water quality supplied by aqueduct service providers. Given the simplicity degree of the index and its basis in compliance or not in relation to maximum limits established by the law, it does not allow analyzing medium- and long-term trends in the drinking water quality supplied. González et al. (2010) also reported that on many occasions the water quality parameters met the legislative limits, but these oscillated very close to the admissibility limit, which reflected deterioration in the drinking water quality provided.

In order to analyze the temporal variations of water quality parameters, statistical models have been developed, which are constituted in an alternative for this purpose. In this regard, we can highlight the models autoregressive integrated moving average (ARIMA). These models have been satisfactorily used in studies to evaluate the water quality in different contexts. For example, Sun and Koch (1996) used ARIMA models to assess the salinity in a bay of Florida (USA). Singh and Bhardwaj (2014) also obtained satisfactory results when analyzing parameters such as pH, BOD, and COD in surface water bodies, demonstrating the effectiveness of ARIMA models to analyze the temporal behavior of these parameters and the realization of forecasts.

The main objective of this paper is to show an operational analysis in a drinking water treatment plant (DWTP) using ARIMA models: 'El Dorado' (Bogota, Colombia). A comparative analysis was carried out between concentrations of water quality parameters, and Colombian legislation and guidelines established by the World Health Organization. We studied the rainfall influence in relation to changes in water quality supplied by the DWTP. A correlation analysis of water quality parameters was also carried out to identify control parameters during the DWTP operation. ARIMA models were developed to study in the short and medium term the DWTP operation. This study was probably constituted as a medium-term planning tool in relation to atypical events or contingencies observed during the DWTP operation.

MATERIALS AND METHODS

Description of the study area

This study was carried out in the DWTP: ‘El Dorado’ (Bogota, Colombia). This DWTP is part of the supply and distribution system of drinking water of the Bogota Aqueduct Company (EAB), which supplies to more than 300000 inhabitants to the south of the city (Hue, 2008). DWTP makes drinking the water from three sequential supply reservoirs: ‘Tunjos’ (2.4 million m^3), ‘Chisaca’ (7.4 million m^3) and ‘Regadera’ (3.3 million m^3). Thus, DWTP makes drinking directly the water collected from the ‘Regadera’ reservoir. Average flow extracted from the ‘Regadera’ reservoir for treatment is 0.4 m^3/s, but the maximum DWTP capacity is 1.6 m^3/s. The treatment system is of conventional type: aeration, coagulation, flocculation, sedimentation, filtration and disinfection using saline electrolysis (MIOX).

Sampling system

Daily information was collected for the following water quality parameters: turbidity, color, electrical conductivity, pH, total alkalinity, chlorides, total hardness, total iron, residual aluminum, free residual chlorine, combined residual chlorine, total residual chlorine, and sulfates. The collection period was between 01/12/2006 and 28/02/2015 (3012 days). The analyses were carried out by the water quality laboratory of EAB.

Information analysis

Phase 1. Information processing and analysis: Initially we evaluated the information representativeness verifying that it counted with more than 75% of data for each one of the time series of water quality parameters considered. A descriptive statistical analysis was also carried out in order to detect trends or anomalies in the time series. A linear correlation analysis was used to evaluate the relationship between water quality parameters in order to establish control parameters or operating indicators of the DWTP. Information processing was carried out using the statistical software IBM-SPSS.

Phase 2. Influence of rainfall periods in the study area: We analyzed the concentration variation of each one of the water quality parameters measured in the DWTP in relation to the rainfall variation in the study area. Daily rainfall information of the ‘Santa Maria de Usme’ climatological station (4°28’52.7” N, -74°7’34.6” W) was provided by the Hydrology, Meteorology and Environmental Studies Institute of Colombia (IDEAM). From the information collected, the decrease and increase periods of rainfall (dry and rainy) were established using the quintiles and classification ranges method proposed by Bolognesi (1971) (Table 1).

Table 1. Classification of dry and rainy periods in relation to monthly rainfall (Bolognesi, 1971)

Climatic period	**Quintile**
Very dry month	$R < Q_1$
Dry month	$Q_1 \leq R < Q_2$
Normal month	$Q_2 \leq R < Q_3$
Rainy month	$Q_3 \leq R < Q_4$
Very rainy month	$R > Q_4$

Note. R = Rainfall

Phase 3: Identification, estimation and verification of ARIMA models: Based on the methodology proposed by Box and Jenkins (1970), ARIMA models were built for daily and weekly moving average timescales. This last timescale was used as an alternative to identify medium-term trends during the DWTP operation due to temporal variability in the water quality information. ARIMA analysis considered the three stages reported by Guerrero (2003): identification, estimation and verification. In the identification stage of ARIMA models, the orders of autoregressive and moving average polynomials were determined, as well as the differentiation degree to cancel the non-seasonality of the time series. In other words, the orders for the terms p, d, and q of ARIMA models were determined. The second stage was aimed at determining values for the parameters $\emptyset_1, \ldots, \emptyset_p$ and $\theta_1, \ldots, \theta_p$ for each ARIMA model identified using the maximum likelihood method. Finally, in the third stage, 8 verification assumptions proposed by Box and Jenkins (1970) were evaluated in order to select the best model to be adjusted to the time series in study.

RESULTS AND DISCUSION

Water quality analysis with reference limits

On average, the daily turbidity of treated water during the study period was 0.27 NTU, with variations between 0.03 and 1.84 NTU (Table 2). This parameter remained within the admissibility limits established by the Colombian law (2.0 NTU) and World Health Organization (WHO, 5.0 NTU). We observed that 0.73% of the data were higher than 1.0 NTU, indicating probably a reduction in efficiency of the purification process during these time intervals. Though, the results obtained were comparatively lower than those reported by similar studies. For example, Akoto et al. (2014) and Farooq and Hashmi (2007) reported in DWTP average turbidity values of 1.10 and 1.0 NTU, respectively.

In relation to pH, an average daily value of 6.95 was observed during the study period. This parameter varied between 5.19 and 9.93 (Table 2). Non-compliances were also observed for 12 days, which exceeded the limits established by the Colombian legislation and WHO guidelines. The results showed that the limits established by the Colombian legislation for pH were more permissive in relation to the WHO guidelines. Non-compliance with pH did not evince a risk to human health but could probably be related to a decrease in efficiency of the DWTP. Akoto et al. (2014) suggested that the failure to comply with this parameter could be mainly related to unitary processes of coagulation and flocculation, or to the lime application in purification process.

On average, the daily concentrations of free residual chlorine were 1.48 mg/l, with daily variations between 0.28 and 2.59 mg/L. The WHO (2011) mentioned that it is common to supply water with concentrations greater than 1.0 mg/L as prevention during the water distribution process, and that adverse effects have not been reported when consuming water with high chlorine concentrations. Thus, concentrations greater than the maximum permissible limit established by the Colombian legislation did not mean a public health risk and could probably be related to the presence of reducing agents in raw water. Ibarguen and Bernal (2008) reported similar results in purification systems.

In relation to the other water quality parameters, the greater variations in order of importance were for the following parameters: total iron, residual aluminum, color, and chlorides. In these water quality parameters, the maximum concentrations observed were 34, 13, 10, and 5 times higher than the average daily concentrations observed (Table 2). The results suggested that the water characteristics supplied by the study DWTP were not constant over time, possibly by the characteristics of raw water treated or by the dosage of reagents used in purification processes. All previous results showed that the water supplied by the DWTP was suitable for human consumption during the study period.

Rainfall influence in the purification process

In the study area, rainfall showed a bimodal regime, where the dry period was observed between January and March, and August and September. Rainy period was observed between April and July, and October and December. The previous trend could be affected by influence of the climatic phenomena of ‘El Niño’ and ‘La Niña’ (ENSO climate phenomenon), which occurred between the years 2010-2011 and 2013-2015, respectively. On average, the daily concentrations of water quality parameters in the DWTP varied in relation to the identified climate periods. For example, during rainy periods the following parameters tended to increase in relation to the dry periods: turbidity, electrical conductivity, total and calcium hardness, total iron, residual aluminum, free residual, combined and total chlorine, and sulfates. On the contrary, the following water quality parameters tended to decrease during rainy periods: color, pH, chlorides, and total alkalinity. Ibrahum and Abu-Shanab (2013) reported a similar trend in relation to the rainfall influence. Figure 1 shows the variation in water turbidity in relation to these two climate periods during the year 2011. On average, during rainy periods the turbidity increased by 15% in relation to dry periods. In these rainy periods, turbidity reached maximum values of up to 0.97 NTU while during the dry periods it did not exceed 0.5 NTU.

Therefore, the results suggested that the purification process efficiency was conditioned by the rainfall variation observed in the study area, probably influencing the physical and chemical characteristics of water collected for the purification process. Romero (2005) reported a similar trend in relation to the increase of turbidity in rainy periods, suggesting the need to increase the coagulant concentration (aluminum sulfate) in the raw water collected for its decrease. This also generated an increase in the concentration of its residuals in the treated water: residual aluminum and sulfates.

Relationship between water quality parameters

Correlation analysis was done under three-time scales: daily, weekly, and monthly. The results showed that the best correlations were observed under the monthly timescale (Table 3). The best correlations in order of importance were observed for the following parameters: chlorides, free residual chlorine, turbidity, electrical conductivity, and total iron. In relation to chlorides, the higher correlations were observed with the following water quality parameters: electrical conductivity (r = 0.68), calcium hardness (r = -0.63), total hardness (r = -0.58), and free residual chlorine (r = -0.52). The previous trend was probably because the water conductivity depended on the dissolved ionized substances concentration, including the chloride ion (Cl^-). Romero (2005) reported similar results in purification systems.

We also observed significant correlations between free residual chlorine and the following water quality parameters: Total iron (r = 0.59), chlorides (r = -0.52), and electrical conductivity (r = -0.46). These results differed in relation to the reports of Barbooti et al. (2010). However, Romero (2005) mentioned that this correlation might be associated with the disinfection process. In this process the chlorine to be an oxidizing agent was combined quickly with Fe present in the water and in turn the free residual chlorine (HOCl) reacted with it to form Fe^{+++}.

Similarly, for turbidity, a direct correlation was observed with total iron (r = 0.54) and color (r = 0.53), and indirect with total alkalinity (r = -0.49) and pH (r = -0.41). This trend probably showed the pH and alkalinity influence on the purification process efficiency in relation to the turbidity elimination. From the relationships exposed, the results suggested in order of importance to the following water quality parameters as the most representative to evaluate the DWTP operation (purification indicators): chlorides, free residual chlorine, turbidity, electrical conductivity, and total iron.

Table 2. Statistics for quality parameters of treated water in the 'El Dorado' DWTP

Parameter	**Unit**	**Minimum**	**Maximum**	**Average**			**Standard deviation**	**Colombian legislation (Res. 2115-2007)**[a]	**WHO**[b]
				Dry-Rainy period	Dry period	Rainy period			
Turbidity	NTU	0.03	1.84	0.27	0.26	0.28	0.14	2.0	5.0
Color	PCU	0.0	18.0	1.76	1.93	1.54	1.29	15.0	15.0
Electrical conductivity	µs/cm	4.69	119	57.3	56.9	57.7	10.3	1000	1000
pH	Units	5.19	9.93	6.95	6.98	6.92	0.28	6.5-9	6.5-8.5
Total alkalinity	mg/L	2.0	22.0	7.61	8.03	7.12	2.06	200	200
Chlorides	mg/L	0.0	21.3	4.6	4.88	2.24	2.46	250	250
Total hardness	mg/L	1.53	39.3	17.4	17.1	17.7	3.17	300	500
Calcium hardness	mg/L	4.79	28.1	15.4	15.1	15.8	2.86	-	-
Total iron	mg/L	0.0	1.01	0.03	0.03	0.03	0,05	0.3	0.3
Residual aluminum	mg/L	0.0	0.93	0.07	0.06	0.07	0.06	0.2	0.2
Free residual chlorine	mg/L	0.28	2.59	1.48	1.47	1.48	0.25	0.3-2	5
Combined residual chlorine	mg/L	0.0	11.0	0.12	0.11	0.13	0.21	-	-
Total residual chlorine	mg/L	0.0	12.1	1.6	1.59	1.61	0.33	-	-
Sulfates	mg/L	0.0	26.4	7.77	7.08	8.63	2.57	250	400

Note. [a] Characteristics, basic instruments and frequencies of the control and monitoring system for water quality of human consumption are indicated (Colombia); [b]: Guidelines for drinking water quality (WHO, fourth edition).

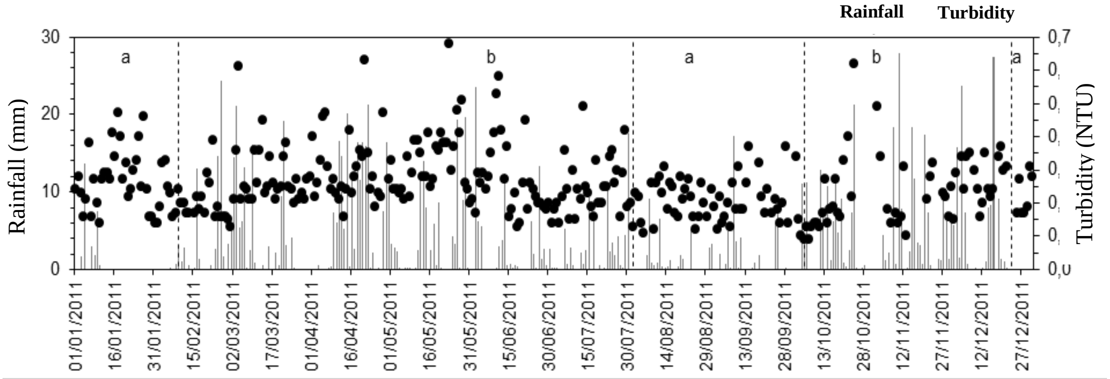

Figure 1. Turbidity variation in the DWTP in relation to rainfall during the year 2011. a) Dry period, and b) rainy period

Table 3. Pearson's linear correlation coefficients between water quality parameters (monthly timescale)

Parameter	TUR	COL	EC	pH	ALK	CHL	HAR	HCA	TI	RA	FRC	CRC	TRC	SUL
TUR	1													
COL	**0.53**	1												
EC	-0.33	-0.19	1											
pH	**-0.41**	-0.08	**0.48**	1										
ALK	**-0.49**	-0.1	0.24	**0.46**	1									
CHL	-0.27	0.09	**0.68**	**0.48**	0.25	1								
HAR	0.2	-0.03	-0.05	-0.22	0.09	**-0.58**	1							
HCA	0.27	0.0	-0.19	-0.25	0.05	**-0.63**	**0.96**	1						
TI	**0.54**	**0.43**	-0.35	-0.33	-0.11	-0.3	0.32	0.37	1					
RA	0.15	0.18	-0.13	-0.31	-0.38	-0.16	0.09	0.04	0.26	1				
FRC	**0.4**	0.34	**-0.46**	-0.29	-0.23	**-0.52**	**0.4**	**0.44**	**0.59**	0.11	1			
CRC	-0.11	-0.29	0.17	0.12	0.03	-0.21	0.19	0.16	-0.12	-0.16	0.05	1		
TRC	0.34	0.24	-0.38	-0.23	-0.21	**-0.54**	**0.43**	**0.46**	**0.52**	0.07	**0.95**	0.36	1	
SUL	0.15	-0.18	**0.5**	-0.03	-0.29	0.0	**0.45**	**0.4**	0.02	0.23	0.01	0.18	0.07	1

Note. TUR: Turbidity, COL: Color, EC: Electrical conductivity, ALK: Total alkalinity, CHL: Chlorides, HAR: Total hardness, HCA: Calcium hardness, TI: Total iron, RA: Residual aluminum, FRC: Free residual chlorine, CRC: Combined residual chlorine, TRC: Total residual chlorine, and SUL: Sulfates. Values in bold correspond to linear correlations higher or lower to 0.40 and -0.40, respectively.

Analysis using ARIMA Models

We determined the ARIMA models (p,d,q) for the daily and weekly moving average timescales from the parameters identified as purification indicators in the study DWTP: chlorides, free residual chlorine, turbidity, electrical conductivity, and total iron. The models obtained to represent the temporal behavior of these parameters are showed in Table 4.

In relation to the autoregressive term (p) of ARIMA models developed, the results showed under a daily timescale that parameters such as total iron and free residual chlorine were not influenced by concentrations of days immediately preceding (ARIMA, p = 0). This trend was probably associated with that these water quality parameters depended on controlled operation conditions to ensure optimum water treatment in the DWTP; specifically, in relation to the pH stabilization and coagulating agent dosage (aluminum sulfate).

Table 4. ARIMA models for operation indicator variables in the DWTP

Parameter	**ARIMA Model^a**		**R^2**	**MAPE^d (%)**	**ARIMA Model^b**		**R^2**	**MAPE (%)**
	(p,d,q)	**Transf.^{c}**			**(p,d,q)**	**Transf.**		
Turbidity	(2,0,5)	Ln	0.578	24.90	(2,1,7)	Ln	0.956	4.709
	(3,0,3)	Ln	0.577	24.89	(3,1,7)	Ln	0.956	4.704
Electrical conductivity	(1,1,12)	Ln	0.856	4.888	(2,1,12)	Ln	0.992	0.949
	(1,0,12)	Ln	0.857	4.854	(2,1,11)	Ln	0.992	0.949
Chlorides	(1,1,3)	R	0.806	20.96	(1,0,16)	Ln	0.984	3.783
	(1,0,3)	R	0.786	21.77	(0,1,16)	Ln	0.984	3.768
Total iron	(0,1,12)	R	0.524	70.41	(1,1,12)	R	0.916	21.04
	(0,1,15)	R	0.525	70.83	(1,1,14)	R	0.916	21.00
Free residual chlorine	(0,1,4)	R	0.400	10.52	(1,1,8)	N	0.969	1.621
	(0,1,6)	R	0.394	10.53	(2,1,7)	Ln	0.968	1.647

Note. ^{a} Daily timescale; ^{b} Weekly moving average timescale; ^{c} Transformation: Ln = Natural logarithm, R = Square root, and N = None; ^{d} MAPE = Mean absolute percentage error.

On the other hand, parameters such as turbidity, electrical conductivity and chlorides showed a short memory under a daily timescale. In other words, concentrations at a specific time depended on concentrations observed between one and two days immediately preceding (ARIMA, $p = 1$ and 2). This was probably related to corrective operation actions during previous days to comply with the permissible water quality limits in the DWTP. For example, these corrective operation actions were probably associated with changes in turbidity according to the rainfall frequency.

In relation to the moving average term of ARIMA models developed, the results showed that concentrations at a specific time were influenced by random events from previous days; specifically, for the parameters of electrical conductivity and total iron. In these water quality parameters, the influence of up to 12 days immediately preceding was observed (ARIMA, $q = 12$ and 15). The foregoing probably could be attributed to the fact that the time-series fluctuations of these water quality parameters were not visible in the short term due to the high variability of concentrations over time. Instead, parameters such as turbidity and chlorides showing a low variability in relation to its average value, showed a lower order for this term in the ARIMA models developed (ARIMA, $q < 5$).

The results showed in relation to the ARIMA models' adjustment that the determination coefficient was elevated ($R^2 > 0.75$) for parameters like electrical conductivity (1,0,12) and chlorides (1,1,3), whereas for turbidity, total iron, and free residual chlorine the determination coefficient was low. Also, in these last water quality parameters was observed a mean absolute percentage error (MAPE) of up to 70% (Table 4). This indicated that the ARIMA models were not adequately adjusted to the time series in study, possibly by variability in the daily information observed.

On a daily basis, the results suggested that fluctuations in the short-term did not allow demonstrating through ARIMA models the temporary structure of the time series of water quality parameters. Therefore, in this study was applied to the daily information a transformation of 7-days moving average (weekly), which allowed to develop ARIMA models of medium-term for purification indicators parameters in the DWTP. The models developed did not show orders greater than 3 in relation to the autoregressive term ($p = 3$), probably showing the operation influence in the DWTP between one and two weeks immediately preceding.

In relation to the moving average term in ARIMA models, the results showed that the variations observed during previous weeks might not be assimilated instantaneously. In other words, these variations influenced the time series after several weeks; as was reported by Guerrero (2003). The results showed better determination coefficients ($R^2 > 0.90$) and lower MAPE (5%) in relation to the ARIMA models developed at weekly level. Except for ARIMA models developed for total iron (1,1,12 and 1,1,14), in which the mean absolute percentage error was greater than 21%. The results suggested that the operative efficiency of DWTP was affected by events that occurred during previous weeks, either by variations in physicochemical characteristics of the water collected (e.g., climate factors), or by the deficiencies detection during its operation (i.e., water quality supplied).

CONCLUSIONS

In this study, the results show the usefulness of ARIMA models to analyze the DWTP operation under a weekly timescale (medium term). In other words, under a daily timescale there are significant variations in the water quality parameters that make it difficult to analyze the DWTP operation in the short term. The application of a 7-day moving average transformation to the daily time series of water quality parameters decreases the mean absolute percentage errors (MAPE) of forecasts generated with ARIMA models. The results suggest the influence of water quality parameter concentrations observed during weeks immediately preceding (between 2 and 3 weeks) on the DWTP operation. In this way, the use of ARIMA models in DWTP is probably constituted in a medium-term planning tool against atypical events or contingencies during its operation. Finally, the results of this study are useful for companies or designers of purification systems in order to take decisions in the public health framework.

ACKNOWLEDGMENTS

The authors appreciate the support of Empresa de Acueducto y Alcantarillado de Bogotá, y Grupo de Investigación en Ingeniería Ambiental de la Universidad Distrital Francisco José de Caldas (Colombia).

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