Assessing Water Quality Characteristics of pH and Biochemical Oxygen Demand (CBOD) of Public Utility using Statistical Quality Control (SQC)

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ABSTRACT

This paper is a continuation of previous research supervised by co-author Segall that appeared in Akarapu et al. (2016a, 2016b) at WMSCI 2016. This research studies in depth only two of the characteristics of water quality for actual 2016 data collected for a water treatment plant located in United States where the previous studies Akarapu et al. (2016a, 2016) studied five characteristics of water quality for 2014 data for the same water treatment plant. The two water quality characteristics studied in-depth with this paper with a more recent data set for the same water treatment plant are pH and Carbonaceous Biochemical Oxygen Demand (CBOD). The claim is that seasonal quadratic trend lines were the most accurate for pH, and pH must be a function of other variables such as Ammonia Nitrogen (NHS-N) and Suspended Solid Bodies (SSB). Discussions of the analyses are presented as obtained using Minitab 17 and Minitab 18.

Keywords: Carbonaceous Biochemical Oxygen Demand (CBOD), pH, Statistical Quality Control (SQC), Suspended Solids, Water Quality

1. INTRODUCTION

1.1 What is pH?

In chemistry, Solutions with a pH less than 7 are acidic and solutions with a pH greater than 7 are basic. Pure water is neutral, at pH 7 (25 °C), being neither an acid nor a base. Contrary to popular belief, the pH value can be less than 0 or greater than 14 for very strong acids and bases respectively. More precisely it is the negative of the base 10 logarithm of the activity of the hydrogen ion. Solutions with a pH less than 7 are acidic and solutions with a pH greater than 7 are basic. Pure water is neutral, at pH 7 (25 °C), being neither an acid nor a base. (APEC (2018))

In general, water with a low pH (< 6.5) could be acidic, soft, and corrosive. The primary way to treat the problem of low pH water is with the use of a neutralizer. Water with a pH > 8.5 could indicate that the water is hard. Hard water does not pose a health risk, but can cause aesthetic problems. These problems include causing an alkali taste to the water and can make coffee taste bitter; and difficulty in getting soaps and detergents to foam and formation of insoluble precipitates on clothing, etc. (APEC (2018))

1.2 What is CBOD?

Biochemical Oxygen Demand (BOD) is a measure of the dissolved oxygen consumed by microorganisms during the oxidation of reduced substances in waters and wastes. Typical sources of BOD are readily biodegradable organic carbon (carbonaceous, CBOD) and ammonia (nitrogenous, NBOD). These compounds are common constituents or metabolic byproducts of plant and animal wastes and human activities (domestic and industrial wastewaters). The discharge of wastes with high levels of BOD can cause water quality problems such as severe dissolved oxygen depletion in receiving water bodies. (Penn et al. (2009))

2. BACKGROUND

This paper is a continuation of previous research presented in Akarapu et al. (2016a, 2016b) with current co-author Segall using a different and more recent data set and more advanced statistical quality analysis techniques. Akarapu et al. (2016a, 2016b) investigated the variables of Ammonia Nitrogen (NH3-N), and Temperature in addition to pH and COBD. The co-author Segall has also completed previous research on quality related modeling with ocean water in Copeland et al. (1991, 1993) and statistical data quality related issues in Jaraiedi and Segall (1990), and Lu and Segall (2011a, 2011b).

Previous work on quality control of wastewater treatment was studied by Aizenchtadt et al. (2008), General Electric Power & Water (2012), Honorota and Costanzi (2013), Liu et al. (2014), Ruiz (2008), Ruiz et al. (2005), Smeti et al. (2007), Spindler (2015), and Thomann (2008), Zurawski (1994). Berthouex (1989) discussed constructing control charts for treatment for wastewater treatment plant operation, and Berthouex et al. (1989) presented a statistics-based system for treatment plant operations.

George et al.(2009) studied fault detection of drinking water treatment process using Hotelling's T^2 chart, Orssatto et al. (2014) studied Stewart's control charts and process capability ratio applied to a sewage treatment station.

Ratnaweera and Fettig (2015) studied the state of the art of online monitoring and control of the coagulation process for water, and Katebi et al. (1999) published a book on control and instrumentation for waste-water treatment plants. Albertville Municipal Wastewater Treatment Plant (2010) in Maine discussed in their Manual of Operations the details of how Statistical Quality Control was utilized for their daily operations.

3. ANALYSIS OF WATER QUALITY USING pH AND CBOD

3.1 pH

Figure 1 shows the Summary Reports for each of the 4 seasons of the 2016 year. Seasons 1 & 3, the two graphs on the left side of the figure, are the most symmetrical plots; seasons 2 & 4 aren't nearly as symmetrical as the other seasons. The mean for each seasons can be seen on the right hand side of each plot including other calculated data values. Seasons 1 & 3 are the most normally distributed data sets on the figure. Note that none of the recorded data values exceed the upper and lower specification limits (USL/LSL).

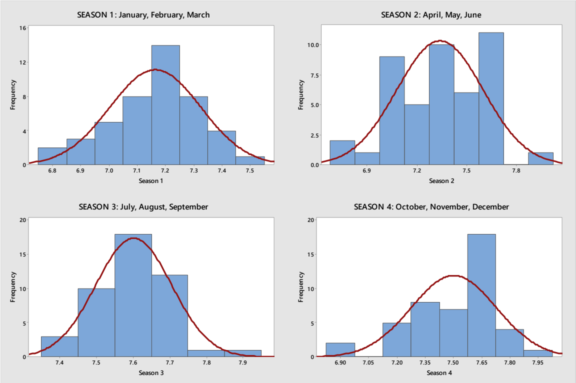


Figure 1: pH Summary Report for each of the 4 seasons of 2016

Figure 2 shows Times Series Plot (Annual) is as stated a Time Series plot of all the recorded 180 pH values measured in the year 2016. The first 90 measurements have a general pH below the CL of 7.5, the next 50 data values of pH hover just over the CL, and the last 45 data values fluctuate almost randomly above and below the CL. For the first few months of 2016 the pH is more centered around 7.0, which is the neutral pH value. This is followed by an increasing linear trend from indices of 54 to 90 corresponding to the months of April, May and June, and why this is cannot be answered currently.

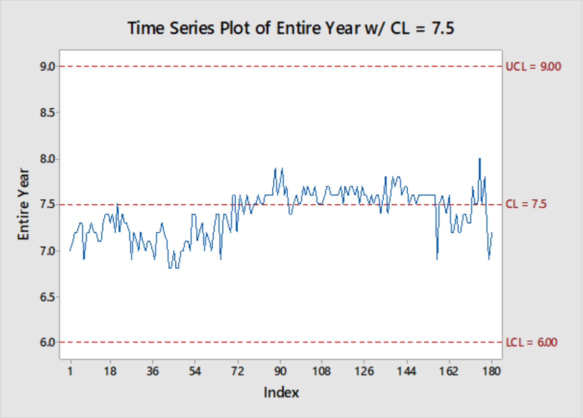


Figure 2: pH Time Series Plot for 2016

Figure 3 shows the collective frequencies of pH values with histograms for each month of 2016. September and December seem to fit the normal distribution very well, but the data set for the month of August is the most symmetrical and includes the least amount of pH variation of the 2016 with only three histogram bars. This is likely associated with the sudden shift of pH in Figure 1. It can be hypothesized that the dramatic increase of pH between April and June influenced the water treatment facility to begin an aggressive neutralization process to effectively moderate and plateau the measured pH.

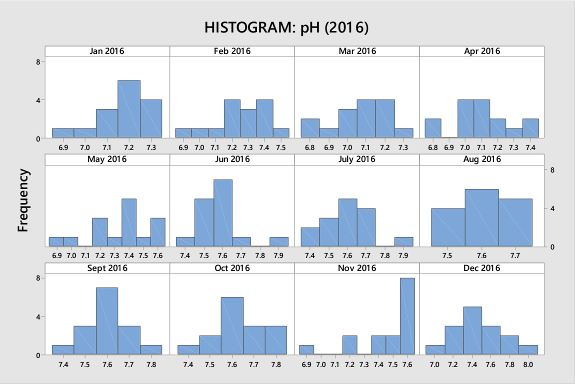
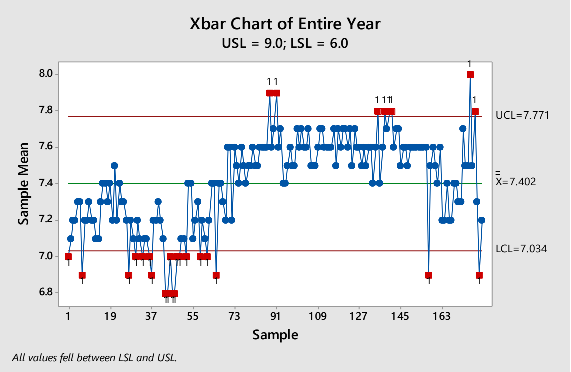


Figure 3: 2016 Monthly Histograms of pH values Frequency

Figure 4 illustrates the variation of the pH from month to month with specified and calculated limits. The specification limits are noted but only the calculated control limits can also be seen within the Figure 4.

Figure 4 contains numerous outliers, however due to the width of the specification band the process is in fact incredibly controlled. The first few months of 2016 have a pH between 7.034 and 7.276, while the latter months of 2016 have a pH between 7.771 and 7.529. The month of May seems to be the transitional period where the pH shifts from relatively neutral to relatively basic. This also suggests that during and following the month of April something occurred which stimulated the dramatic increase in pH. This variation of pH must be directly related to the introduction/removal of something in a large capacity to cause such a steep incline in pH.



All values fell between LSL and USL.

Figure 4: pH X-Bar Control Chart of 2016 year

Individual Moving Range (I-MR) is a type of Control Chart that is often used for continuous data. The I-MR chart was developed initially by Walter Shewart and hence the control charts are sometimes also referred to as Shewart Charts. [25]

With I-MR we have two charts – one with Individual data points (Individual Chart/I-Chart) and the other with the respective range between each consecutive individual point (Moving Range Chart/MR-Chart). The two charts are useful together and using only one may not give the complete information on the behavior of the process. [25]

Figure 5 is an I-MR control chart with 2016 data with I-chart at the top and MR-chart on the bottom of this figure. The LCL of the MR plot on the bottom of Figure 5 is zero and none of the data points are below this. The majority of the data points are within the control limits of both the I-chart and MR-chart and hence it can be concluded that the process can be interpreted as being in control.

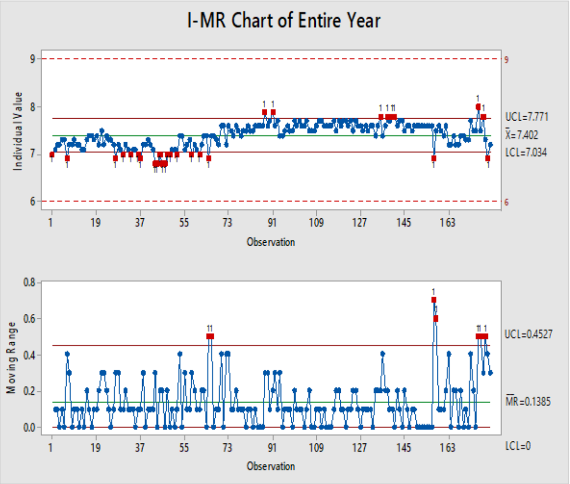


Figure 5: pH I-MR (Individual Moving Range) Chart for 2016 Year

A trend-line analysis was performed on the 2016 pH data set. The quadratic polynomial relationship was determined to be the best fit for each of the 4 seasons of the 2016 annual pH values. Due to variation within each season, the quadratic trend of each of the 4 seasons is illustrated as in Figure 6 instead of singularly using the entire 2016 annual data set. Figure 6 provides us with the quadratic trend-lines of each of the 4 seasons. If the seasonal trend-lines were to overlay the annual quadratic trend-lines on a singular plot it would become apparent the seasonal quadratic trend better represents the accumulated data.

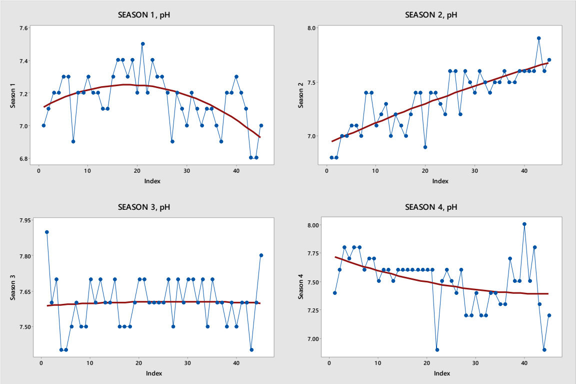


Figure 6: pH Quadratic Trend Models for 4 seasons of 2016

Figure 7 displays the seasonal run chart as opposed to an annual run chart. Much like the time series and x-bar plots, the run chart also shows an initial steady decline where at April a steady increase gives rise to a relatively stable 3rd season. It can also be inferred that the 4th season has a relatively stable pH through October but as it progresses toward the end of the year, the pH actually becomes more volatile and begins erratically fluctuating about its mean.

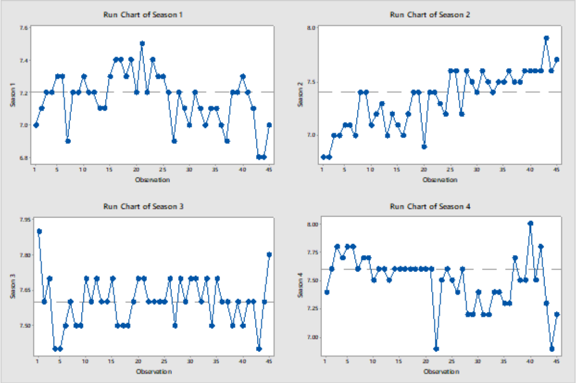


Figure 7: pH Run Charts (4 Seasons of 2016)

Figures 8 and 9 are overlaid plots of the monthly means of Ammonia-N and Suspended Solid Bodies (SSB) and pH, respectively. When the monthly means are plotted obvious correlations can be inferred by simply eyeing both sets of the data on each overlaid plot. Both data sets display a near perfect inverse proportion to one another, this aspect is best visible from June to December (6 to 12, horizontal-axis).

The plotting of the overlaid graphs was initially done to check if any correlation existed, and if so was it visibly noticeable. Yes, Ammonia-Nitrogen content and Suspended Solid Bodies (SSB) content are independent and each directly affect the pH concentration of the water being measured. Since pH is a dependent characteristic, a claim can be made that the pH is directly dependent on the concentration of both the Ammonia-Nitrogen and SSB within a body of water.

On a separate note, the steep increase in pH over the 5th month (May) seems to be visibly more associated with the dramatic decline of the Suspended Solid Bodies (SSB) in Figure 9 content rather than the Ammonia-Nitrogen trend over the month of May in Figure 8.

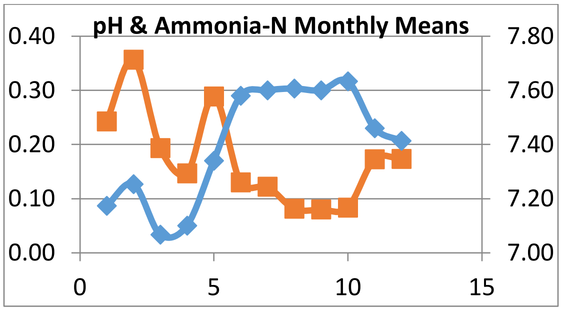


Figure 8: Overlaid pH & Ammonia-N Means (Monthly, 2016)

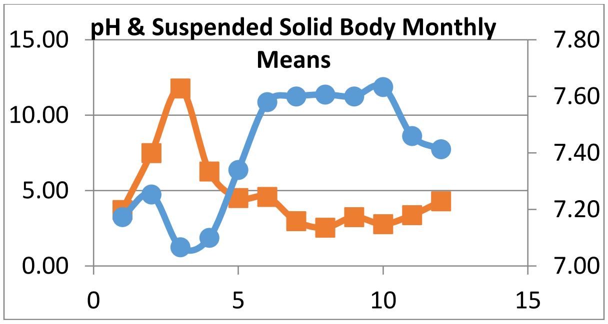


Figure 9: Overlaid pH & Suspended. Solid Body Means (Monthly, 2016)

Figure 10 illustrates a three-dimensional plane of the variables all together. Ammonia-N, Suspended Solid Bodies, and the pH are all plotted to generate a piece of fabric-like terrain that is not (visibly) incredibly unstable. Because the surface plot more closely resembles a valley rather than an incredibly mountainous region it can be safe to again claim that pH is dependent on the concentration of Ammonia-Nitrogen and Suspended Solid Bodies (SSB); however, more data is needed to justify the claim.

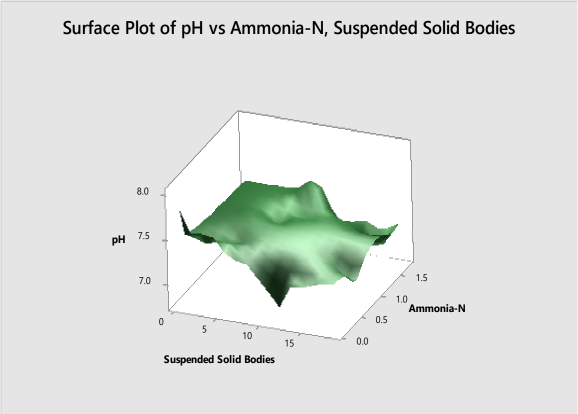


Figure 10: Surface Plot of pH, Ammonia-N, and Suspended Solid Bodies (2016 year)

Figure 11 is Process Capability Report of pH, A-N, SSB (Annual) and provides almost concrete evidence that the pH is heavily dependent on the concentrations of Ammonia-N and the Suspended Solid Body data provided. The normal probability plot shows just how great the correlation is between all the variables.

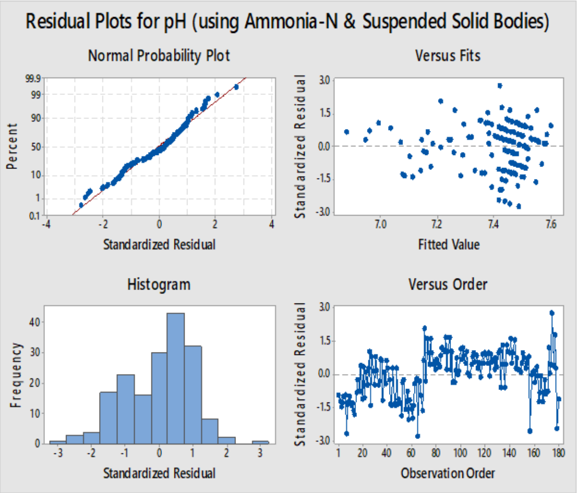


Figure 11: Process Capability Report of pH as a function of Ammonia-N and Suspended Solid Bodies) (2016)

3.2 Carbonaceous Biochemical Oxygen Demand (CBOD)

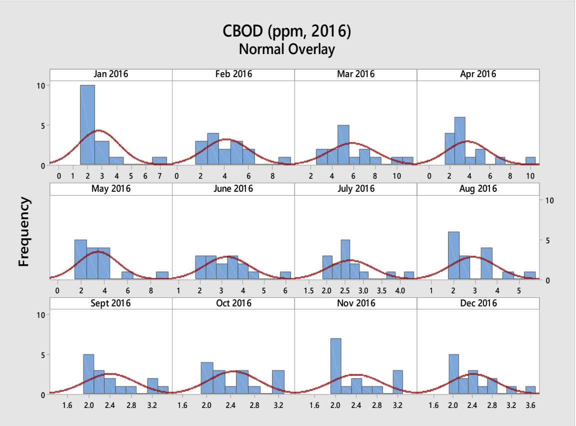


Figure 12: CBOD, Monthly Histogram (2016).

A histogram is a graphical representation of the distribution of numerical data. The above histogram plot of CBOD effluent is a graphical representation of the frequency of data points for the entire year of 2016. Note that the vertical axis is occurrences, the horizontal axis represents CBOD. The CBOD values range from 2.0 to 10.7. The maximum value occurs in March (10.7 ppm), however the minimum value occurs numerous times throughout 2016. The data is in the acceptable range for the CBOD effluent values, as 15 ppm is the max allowable limit specified from the water quality plant.

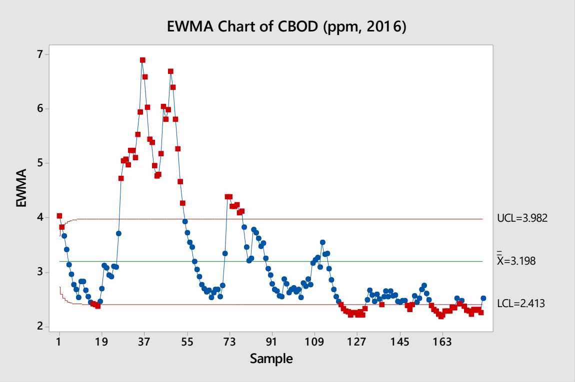


Figure 13: EWMA Chart of CBOD Effluent (2016)

The EWMA chart (exponentially weighted moving average chart) is a type of control chart used to monitor either variables or attributes-type data. The above Figure 13 represents the data values of CBOD effluent for 2016. The EWMA chart is sensitive to small shifts in the process mean, it is observed that more oscillations with respect to small changes in data values for CBOD effluents for year 2016. During the month of March, the process is mean is substantially higher, which means the process was in control the entire year of 2016, except for the month of March. Further data is needed to understand why this occurred.

A residual plot is a graph that shows the residuals on the vertical axis and the independent variable on the horizontal axis. Figure 14 reveals that the residuals are reasonably normally distributed when SSB is used as an estimator for CBOD. This suggests a relationship between SSB and CBOD should exist.

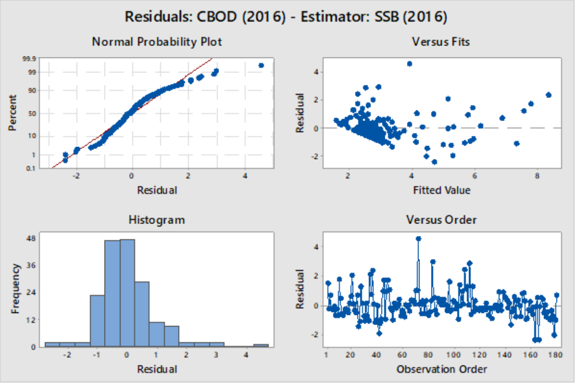


Figure 14: Residuals-CBOD, Estimator-SSB (2016)

Figure 15 reveals a relationship between CBOD, SSB, and the year of 2016. The contour plot reveals that the CBOD is relatively high when the SSB are also relatively high. This occurs between beginning of February and the end of March.

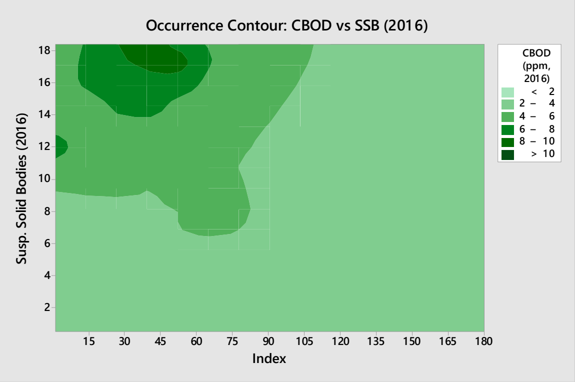


Figure 15: CBOD Contour Plot vs SSB (2016).

4. CONCLUSIONS

This research has illustrated the usefulness of statistical quality control and its various control charts for assessing water quality characteristics of pH and CBOD. For pH it was noted that seasonal quadratic trend lines were the most accurate, and pH must be a function of other variables such as Ammonia-Nitrogen and Suspended Solid Bodies (SSB) that were also available to us in this study of real 2016 water quality data. There is a strong relationship between CBOD and SSB for 2016 and this was especially pronounced for the month of March. Further study needs to be done to explain why this has occurred and if this is a trend for more current or future year’s data.

5. ACKNOWLEDGEMENTS

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