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Monitoring and Improvement of Water Treatment Process Based On Multivariate Statistical Process Control Techniques

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Abstract: Water quality monitoring and evaluation provides important information to estimate water system status. Clean water prolongs someone's life through equitable health facility. Residents suffer of unclean water service provided by the utility Service provider due to lack of sophisticated methods of treatment. This research seeks to monitor and improve the water treatment process at various stages. In this regard, multivariate statistical process control (MSPC) techniques specifically, the multivariate exponentially weighted moving average (MEWMA), the Hotelling's T^2 and the ellipse control charts have been applied to water statistical data. Monitoring was centred only on two basic water parameters namely; total suspended solids (TSS) and biochemical oxygen demand (BOD). These two parameters play a pivotal role in the composition of quality drinking water and they normally exhibit a high correlation. Results show that the process of treating water for human consumption is not statistically in control hence requires improvement.
Keywords: MSPC; water; treatment; monitoring and improvement; control charts.

INTRODUCTION

"Water is life", we always say this but the phrase leaves much to be desired bearing in mind that not every consumed water is safe to drink. Contamination is a great risk to our water; especially surface water where pathogenic bacteria and microbes flourish.

Contamination can be chemically (heavy metals from industry, synthetic fertilizers and poisonous minerals, etc.), biological (pathogenic bacteria and microbes) and physically (human and animal waste disposal). Drinking contaminated water causes different chronic or acute diseases, which may shorten life span. Therefore these substances are supposed to be removed from the waste water by means of water purification through treatment before the water is supplied to consumers. The treatment process of drinking water involves the removal of contaminants from raw water to come up with water that is pure enough for human consumption, free from health hazards. Substances that are removed during the treatment process include suspended solids, bacteria, algae, viruses, fungi, and minerals such as iron and manganese.

This article draws attention to drinking water treatment processes from the effluent dam of wastewater to a treatment plant where consumers have been complaining about the quality of water coming from their taps. Service providers are mandated to bring sanity in the provision of safe and clean water to the consumers to promote good health. A dam is the main source that supplies water to the treatment plant and subsequently to all the residents around. Water is pumped from the dam to treatment plant for treatment. This involves the abstraction of water from the water source and raw water is pumped to the treatment plant; where suspended particles are settled by the addition of alum sulphate to help quicken the settling process. After the particles have settled under sedimentation which is the second stage, they are removed and water is filtered using slow sand filters under the filtration stage. When water filtration is done, water is pumped to the next tank where chlorination or disinfection takes place. From chlorination tank, water is pumped to the supply tank where the final tests are done to check whether the water to be supplied meets the standard measurements and safer to drink. Currently, the Service provider uses granular chlorine instead of gas chlorine. Tests are further carried in the water network, for example, in the supply pipes and from the taps in case of contaminations which may have taken place in the water supply networks. However, despite all the above processes which seem appealing and standardised for conventional water treatment, residents have been supplied with water which is not safer to drink, confirmed even by eye inspection. Water supplied to consumers especially in the early hours of some days is brownish in colour and comes with unpleasant smell. The water also at times contains some particles which affect its turbidity. This has always raised concerns by the consumers who are in the catchment area. It is believed that the water is associated with the presence of living microscopic organisms; or decaying organic matter including weeds, algae; or industrial wastes containing ammonia, phenols, halogens, and hydrocarbons. Lack of proper control and monitoring of the water treatment process does not only cause the financial losses, but also can cause loss of life.

LITERATURE REVIEW

Multivariate Statistical Technique is an important tool for monitoring and improvement of the quality of products [16]. In recent years, the importance of multivariate Statistical Technique has increased because more quality features are measured in mass production than ever before. These quality measures often exhibit substantial cross-correlations. Statistical Process Control (SPC) and statistical quality control (SQC) refer to a collection of statistically based techniques that rely on quality control charts to monitor product quality [27]. The main objective of Statistical Process Control is to use process data and statistical techniques to determine whether the process operation is normal or abnormal [6]. A process is said to be controlled when, through use of past experience, one can predict at least approximately the probability that the observed values of a product characteristic (also called process output or product parameter) will fall within given limits [26]. The root cause of an out of control process is referred to as the assignable cause or the special cause while the normal process variability is referred to as common cause or chance cause [18].

MSPC has been widely applied in various fields of operation which are industrialized in nature, for example; in mining and processing [13,14,17], in beer industry [15], in engineering [9,13,30] and in wastewater treatment plant (WWTP) [1,20,22,24,28]. The paper published by Praus *et al*. [21] explains the use of multivariate control charts in water treatment data analysis. According to them the water treatment data sets contains not only important information for quality assessment and/or treatment technology but also confusing noise. They further demonstrate in the research paper that multivariate statistical process control through the use of control charts easily provides an unbiased view of water composition and thus can be used as a very useful tool for water quality assessment.

George *et al.* [8] develop a Principal component analysis (PCA) model and a Hotelling's T^2 chart in order to monitor water treatment processes at United Utilities Multistage Water Treatment Works. Their results show that Multivariate Statistical Process Control (MSPC) techniques such as PCA, and control charts such as Hotelling's T^2, can be effectively applied for the early fault detection of continuous multivariable processes such as Drinking Water Treatment (DWT).

Akarapu *et al*. [2] study and monitor five characteristics of water quality using techniques of statistical quality control to data collected at a water treatment plant in United States. They consider only characteristics of Ammonia Nitrogen (NH3-N) that is; pH, Total Suspended Solids (TSS) and Carbonaceous Biochemical Oxygen Demand (CBOD) or Biochemical Oxygen Demand (BOD) and Temperature. Control charts were constructed for each parameter and the results were presented to the company responsible for the data.

Garcia *et al*. [7] propose an approach to deal with the fault detection and diagnosis using multivariate statistical techniques, concretely, the principal component analysis (PCA) is used in detection tasks and the Fisher discriminant analysis (FDA) is implemented in diagnosis tasks. The approach has been proved in a simulated wastewater treatment plant (WWTP) based on the COST benchmark. The used approach shows good results because the faults was detected and correctly diagnosed.

In another paper published by Alberto [3], a biological batch process for the treatment of wastewater has been used to develop and test the supervision method. Multivariate Statistical Process Control (MSPC) methods have shown to be effective in detecting and diagnosing events that cause a significant change in the dynamic correlation structure among the process variables.

Residue and Total Suspended Solids (TSS)

The term residue applies to the substances remaining after evaporation of a water sample and its subsequent drying in an oven at a given temperature. Residue is approximately equivalent to the total content of dissolved and suspended matter in the water since half of the bicarbonate (the dominant anion in most waters) is transformed into CO_2 during this process. In other Words Total suspended solids are the solids retained on a standard filter (usually a glass fibre GF/C grade) and dried to a constant weight at 105^0C. Solids can be defined as the term widely used for the majority of compounds which are present in natural waters and remain in a solid state after evaporation. Some organic compounds will remain in a liquid state after the water has evaporated. Total suspended solids (TSS) and total dissolved solids (TDS) correspond to non-filterable and filterable residue respectively.

Biochemical Oxygen Demand (BOD)

The biochemical oxygen demand (BOD) is an approximate measure of the amount of biochemically degradable organic matter present in a water sample. BOD can also be defined as the amount of oxygen required for the aerobic micro-organisms present in the sample to oxidise the organic matter to a stable inorganic form. The method is subject to various complicating factors such as the oxygen demand resulting from the respiration of algae in the sample and the possible oxidation of ammonia (if nitrifying bacteria are also present). The presence of toxic substances in a sample may affect microbial activity leading to a reduction in the measured BOD [23]. The conditions in a BOD bottle usually differ from those in a river or lake. Therefore, interpretation of BOD results and their implications must be done with great care and by experienced personnel. The BOD test can be used to determine the treatability of effluents by biological treatment processes [19].

Water Purification Processes

According to WHO/UNICEF joint monitoring report [29], water treatment involves the removal of contaminants from raw water to produce water that is pure enough for human consumption without any short term or long term risk of any adverse health effect. The substances that are removed during the process of water treatment include suspended solids, bacteria, algae, viruses, fungi, and minerals such as iron and manganese. The processes involved in removing the contaminants include physical processes such as settling and filtration, chemical processes such as disinfection and coagulation and biological processes such as slow sand filtration. Below are the major processes which the Service provider undertakes in purifying water from the dam to the residents.

Coagulation and Flocculation

Coagulation and flocculation play a dominant role in many water and wastewater treatment schemes. Groundwater and surface water contain both dissolved and suspended particles. Coagulation and flocculation are used to separate the suspended solids portion from the water. Flocculation is a process where colloids come out of suspension in a solute, such as water. Coagulation is the process whereby a given system may be transformed from a stable to an unstable state [5]. Coagulation is the phase in the overall process whereby the constituents of given water are destabilized and flocculation is the phase whereby destabilized particles, or particles formed during destabilization, are induced to collect into aggregates [5]. Coagulation and flocculation occur in successive steps, allowing particle collision and growth of floc. This is then followed by sedimentation. If coagulation is incomplete, flocculation step will be unsuccessful, and if flocculation is incomplete, sedimentation will be unsuccessful. Coagulation process has the ability to eliminate many pollutants from surface and drinking water, the success of the process has a direct impact on the reliability of treatment plant operations and final water quality [31].

Sedimentation

Waters exiting the flocculation basin may enter the sedimentation basin, also called a clarifier or settling basin. Bahri [4] defines sedimentation as a process in which contaminants that are heavier than water sink to the bottom of a basin and the water is then led out of the basin above the sediment layer. This is a large tank with low water velocities, allowing floc to settle to the bottom. The sedimentation basin is best located close to the flocculation basin so that the transit between the two processes does not permit settlement or floc breaks up. As particles settle to the bottom of a sedimentation basin, a layer of sludge is formed on the floor of the tank which must be removed and treated. The amount of sludge generated is significant, often 3 to 5 percent of the total volume of water to be treated. After a visit to one of the treatment plants, it was observed that the sedimentation basin may be equipped with mechanical cleaning devices that continually clean its bottom, or the basin can be periodically taken out of service and cleaned manually.

Filtration

Filtration is one of the key stages in the water treatment process since it involves the filtering out of large materials from waste water and other non-degradable materials [29]. The most common type of filter is a rapid sand filter. Water moves vertically through sand which often has a layer of activated carbon or anthracite coal above the sand. The top layer removes organic compounds, which contribute to taste and odour [25]. Most particles pass through surface layers but are trapped in pore spaces or adhere to sand particles. Effective filtration extends into the depth of the filter.

Disinfection/ Chlorination

The final stage in water treatment is the disinfection or the chlorination stage. Water is disinfected to kill any pathogens which pass through the filters and to provide a residual dose of disinfectant to kill or inactivate potentially harmful micro-organisms in the storage and distribution systems. Disinfection is accomplished both by filtering out harmful micro-organisms and also by adding disinfectant chemicals. The most common disinfection method involves some form of chlorine or its compounds such as chloramine or chlorine dioxide.

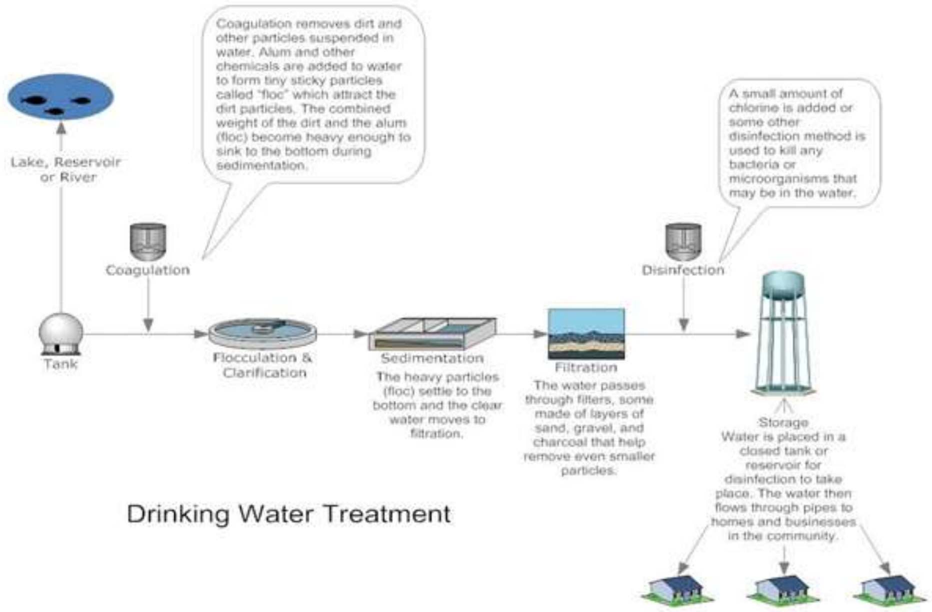

Fig-1: **Summary of stages involved in water treatment. Adopted from WHO [28]**

In this regard, this research article seeks to explore the application of multivariate statistical process control (MSPC) tools to monitor and improve the stability and variability of parameter measurement in water treatment processes. We have showed some interests particularly in three MSPC charts namely; the multivariate exponentially weighted moving average (MEWMA) charting, Hotelling's T^2 and the Control Ellipse. Parameters in water treatment management are numerous but we have looked into two main parameters, that is total suspended solids (TSS) and Biochemical oxygen demand (BOD) in the final water sample ready for consumption. These two parameters were monitored and controlled through the use of MSPC charts mentioned above

MATERIALS AND METHODS

Research Data and Determination of Variables

In this research, daily data on the quality of water supplied was collected from the quality department of one the Service providers in Zambia for 90 days. We were concerned with two main water parameters to monitor and improve the drinking water treatment process. Even though water quality parameters are so many as indicated in Table 1 below, our research is centred on biochemical oxygen demand (BOD) and total suspended solids (TSS). These two variables were chosen due to the important role they play in the composition of quality drinking water. Each water parameter has pre-set limits upon which it should not breach. However, Environmental council of Zambia (ECZ) has set standards to guide the water utility companies in the water treatment process in terms of parameter requirements. According to ECZ, BOD should not exceed 50mg/l and TSS should not exceed 100mg/l. ECZ does not specify the lower limits for these parameter indicators.

Table-1: **Water parameter specifications**

Parameter	Lower Limit	Upper limit
Ph	6	9
Odour	Unobjectionable	-
Dissolved oxygen	4	5mg/l
Total hardness ($CaCO_3$)	300	600mg/l
Chlorides	250	1000mg/l
Dissolved solids	50	200mg/l
Calcium	75	200mg/l
Colour	5	25H
Turbidity	5	10 NTU
Iron	0.04	0.3mg/l
Manganese	0.1	0.3mg/l
Zinc	5	15mg/l
Chlorine	140	250mg/l
Copper	0.05	1.5mg/l
Sulphate	200	400mg/l
Taste	Agreeable	-
Fluoride	1	1.5mg/l
Mineral oil	0.01	0.03mg/l
Boron	1	5mg/l
Aluminium	0.03	0.2mg/l
BOD	-	50mg/l
TSS	-	100mg/l

Determination of Total suspended solids (TSS)

Suspended Solids determination is based on gravimetric measurement after following the appropriate procedures, i.e. filtration, evaporation, drying and ignition. Samples were kept in hard-glass bottles until analysis was performed. In other samples polythene bottles were used so that suspended material could not stick to the walls of the bottle. To help prevent precipitation occurring in the sample bottles, the bottles were completely filled and then analysed as soon as it was possible after collection. A well-mixed sample was filtered through a pre-weighed glass filter. The filter was then dried in a drying oven and reweighed. The weight gain represented the total suspended solids. It is always expressed in mg/l.

Determination of Biochemical oxygen demand (BOD)

Standardised laboratory procedures were used to determine BOD by measuring the amount of oxygen consumed after incubating the sample in the dark at a specified temperature, in this case it was at 20^0C, for a specific period of five days. This gives rise to the commonly used term BOD_5. The oxygen consumption was determined from the difference between the dissolved oxygen concentrations in the sample before and after the incubation period and the initially recorded value. It is important to note that if the concentration of organic material in the samples is very high, samples may require dilution with distilled water prior to incubation so that the oxygen is not totally depleted. Water samples collected for BOD measurement were checked to ensure that they do not contain any added preservatives and were stored in glass bottles. Ideally the samples should be tested immediately since any form of storage at room temperature can cause changes in the BOD (increase or decrease depending on the character of the sample) by as much as 40 per cent.

Hotelling's T^2 Statistic

We proposed Hotelling's T^2 Statistic as a process control chart to monitor biochemical oxygen demand and total suspended solids in the water treatment process. The Hotelling's T^2 chart is a multivariate Shewhart type control chart that only takes into account the present information of the process so as a result, it is relatively insensitive to small and moderate shifts in the process mean vector [10]. The upper control limit for the T^2 control model in phase II is given by:

$$UCL = \frac{p(m+1)(n-1)}{mn-m-p+1} F_{\alpha,p,mn-m-p+1} \quad (1)$$

Where p is the number of parameters being considered and m and n are sample sizes.

In this regard, T^2 has emerged as an important metric for multivariate process control. One assumption to using Hotelling's T^2 statistic to describe the behaviour of statistical distance is the observation vector must follow a multivariate normal distribution. Under this assumption (x_1, x_2) can be described as a bivariate normal using metric notation:

$$(x-\mu)'\Sigma^{-1}(x-\mu) = SD^2 \quad (2)$$

Where $x' = (x_1, x_2)\mu' = (\mu_1, \mu_2)$ and Σ^{-1} is the inverse of the covariance matrix. This formula is the quadratic form of vector $(x-\mu)$ that represents the statistical distance. Therefore, equation (3) is known as Hotelling's T^2 statistics.

$$T^2 = n(\bar{x}-\mu)'S^{-1}(\bar{x}-\mu) = SD^2, \quad (3)$$

where $\bar{x} = \frac{1}{n}\sum_{j=1}^{n} X_j$, S is the covariance matrix and μ is the mean vector.

Control Ellipse

In order to identify samples which were out of the 95 percent confidence interval, a control ellipse was used under multivariate hotelling analysis. The process-monitoring for water treatment was represented by a control ellipse. Let μ_1 and μ_2 be the mean values of the quality characteristics, and let σ_1 and σ_2 be the standard deviations of x_1 and x_2 respectively. The covariance between x_1 and x_2 is denoted by σ_{12}. If $\bar{x}_1$ and $\bar{x}_2$ are the sample averages of the two quality characteristics computed from a sample of size n, then the statistic;

$$x_0^2 = \frac{n}{\sigma_1^2\sigma_2^2\sigma_{12}^2}[\sigma_2^2(\bar{x}_1-\mu_1)^2 + \sigma_1^2(\bar{x}_2-\mu_2)^2 - 2\sigma_{12}^2(\bar{x}_1-\mu_1)(\bar{x}_2-\mu_2)] \quad (4)$$

will have a chi-square distribution with 2 degrees of freedom.

Let us consider two identical and independent random variables x_1, x_2 that is, $\sigma_{12} = 0$, then equation (4) defines an ellipse with centre (μ_1, μ_2) with principal axes parallel to the X_1, X_2 axes. A value of x_0^2 inside the ellipse indicates that the process is in control otherwise it will be out of control. However, our two variables in this research are dependent. The principal axes of the ellipse are no longer parallel to the X_1, X_2 axes. The true probability region is elliptical in nature, and the process is judged out of control only if the pair of means X_1 and X_2 plots is outside elliptical region or judged in control if the pair of means plots is inside the elliptical region.

Multivariate Exponentially Weighted Moving Average (MEWMA) control chart

Multivariate Exponentially Weighted Moving Average (MEWMA) control chart was used to monitor biochemical oxygen demand and total suspended solids in the water treatment process. The main reason we chose this technique is due to its sensibility in detecting non-random changes in the process and based on the principle of the weighted average of the previously observed vectors. The MEWMA chart takes into account the present and past information of the process. Therefore, the MEWMA chart is more powerful to detect small shifts than the Hotelling's T^2 chart [10]. The formula as proposed by Lowry *et al*, [12] is as follows: Let $\boldsymbol{X}_t'$ be the t^{th}, p-dimensional observation. Also assume that $\boldsymbol{X}_t$ follows a $N_p(\boldsymbol{\mu_0}, \boldsymbol{\Sigma_0})$ with a known variance-covariance matrix Σ_0 and a known p-dimensional mean vector μ_0.

$$\boldsymbol{Z}_t = \boldsymbol{R}\boldsymbol{x}_t + (\boldsymbol{I}-\boldsymbol{R})\boldsymbol{Z}_{t-1} = \sum_{j=1}^{t} \boldsymbol{R}(\boldsymbol{I}-\boldsymbol{R})^{t-j}\boldsymbol{x}_j, \quad (5)$$

for $t = 1,2,...$ where $\boldsymbol{R} = diag(r_1, r_2, r_3, ... r_p)$, and $0 < r_1 < 1$ for $k = 1,2,...,p$ and $\boldsymbol{I}$ is the identity matrix. The initial $\boldsymbol{Z_0}$ is usually obtained as equal to the in-control mean vector of the process. It is obvious that when $\boldsymbol{R} = \boldsymbol{I}$, then the MEWMA control chart is equivalent to the T^2 - chart. The MEWMA gives an out-of-control signal if,

$$\boldsymbol{Z_t'} \sum\nolimits_{Z_t}^{-1} \boldsymbol{Z_t} > h$$

Where $\sum_{Z_t}$ is the variance-covariance matrix of $\boldsymbol{Z}_t$. The value h is calculated by simulation to achieve a specified in-control ARL. The MEWMA chart is generally used in the phase *II* with individual data and uses the charting statistic,

$$T_t^2 = \boldsymbol{Z_t'} \sum\nolimits_{Z_t}^{-1} \boldsymbol{Z_t}, t = 1,2,3,... \quad (6)$$

Where

$$\boldsymbol{Z_t} = \lambda\boldsymbol{x}_t + (1-\lambda)\boldsymbol{Z}_{t-1}.$$

The covariance matrix is given by:

$$\sum\nolimits_{Z_t} = \frac{\lambda}{2-\lambda}[1-(1-\lambda)^{2t}]\Sigma \quad (7)$$

with the scalar charting constant λ, $0 < \lambda < 1$ $\boldsymbol{x_t}$ is the vector of observations at time t and $\boldsymbol{Z_0} = \boldsymbol{0}$.

RESULTS AND DISCUSSION

Correlation Analysis of BOD and TSS

Correlation analysis of BOD and TSS parameters was performed to investigate the relationship between these two variables. We have mentioned earlier that the MEWMA chart works well when variables of interest are correlated in some way. The results of the relationship are displayed in figure 2. There is a moderate positive relationship between BOD and TSS with coefficient of correlation being 0.63 and a probability value of 0.000.

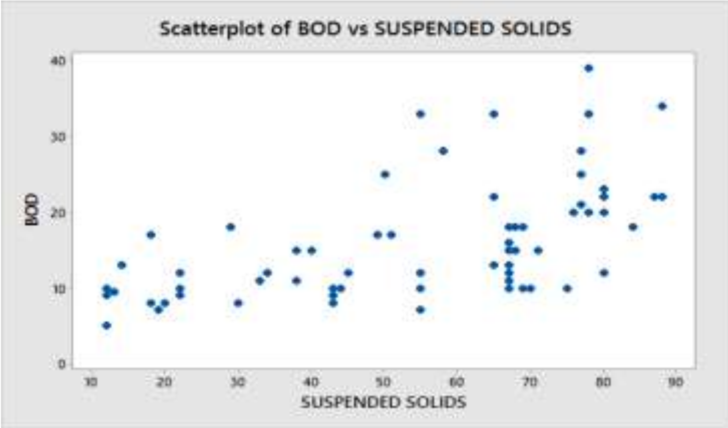

Fig-2: **Scatter plot of BOD and TSS**

Multivariate Exponentially Weighted Moving Average Charts

The control charting was done using MEWMA charts to indicate if there are any disparities in the water treatment process. The chart was adjusted to different average run length (ARL) with two different scales. Firstly, the weight scale was adjusted to $\lambda = 0.2$ with ARL starting from 10. Average run length is the number of samples required before the process becomes in control. In other words we need to seek for a number of samples for our experiment adequate enough to detect an out of control signal. The more power the chart is in detecting faults, the better it is [12]. Figure 3 shows that the process of treating water is out of control (OOC) indicated by red points which are protruding above the upper control limit (UCL). We need at least 46 samples for monitoring before we could get an in control (IC) process.

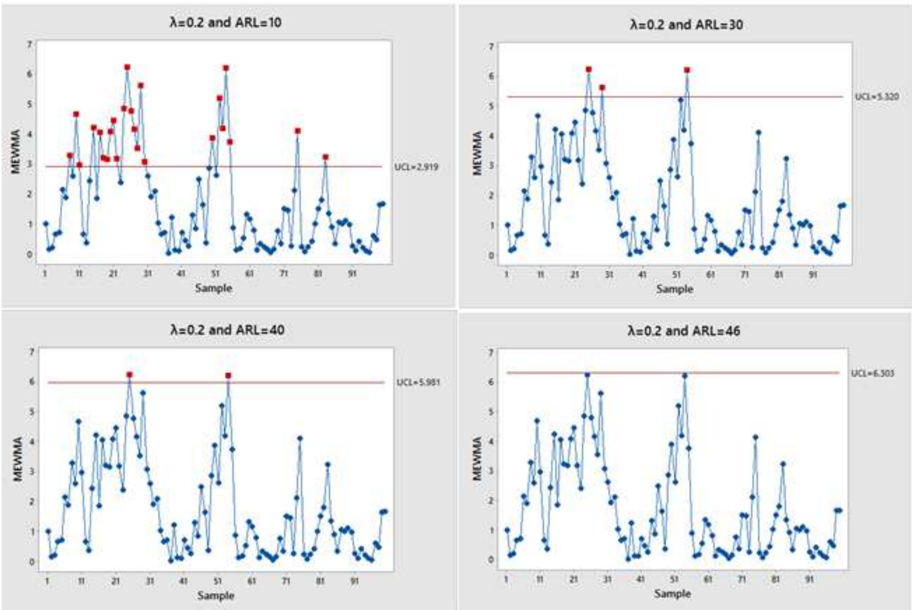

Fig-3: **MEWMA chart with weight $\lambda = 0.2$**

The results in figure 3 are summarised in Table 2 below.

Table-2: **Summary of results of the MEWMA chart with weight** $\lambda = 0.2$

Weight	ARL	OOC	OOC %	IC %
0.2	10	28	31	69
0.2	12	25	28	72
0.2	16	14	16	84
0.2	18	10	11	89
0.2	20	8	9	91
0.2	24	5	6	94
0.2	30	3	3	97
0.2	36	2	2	98
0.2	40	2	2	98
0.2	44	2	2	98
0.2	46	0	0	100

We have also adjusted the weight scale of our MEWMA chart to 0.1 in order to investigate the strength it would have in detecting OOC signals. Results in figure 4 indicate that it takes more samples before the process is in control. In other words, this chart requires more samples to detect an OOC signal than the previous one. It is a little bit slower in detecting the faulty signals. Generally, all these charts are indicating that the water treatment process is out of control.

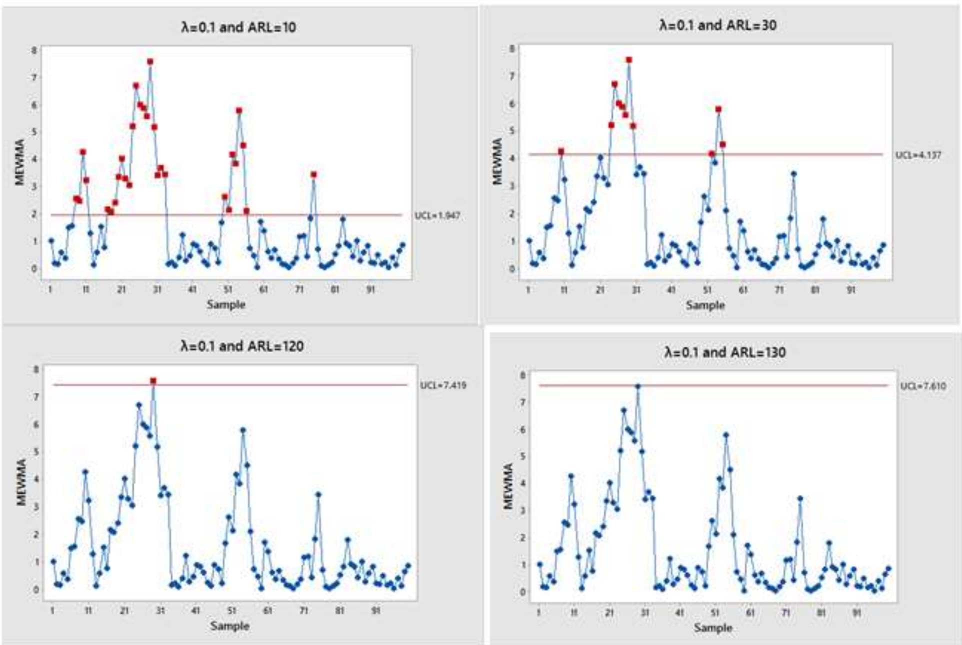

Fig-4: MEWMA chart with weight $\lambda = 0.2$

Table-3: **Summary of results of the MEWMA chart with weight** $\lambda = 0.1$

Weight	ARL	OOC	OOC %	IC %
0.1	10	29	32	68
0.1	18	21	23	77
0.1	24	14	16	84
0.1	30	11	14	86
0.1	40	8	10	90
0.1	48	5	9	91
0.1	55	5	9	91
0.1	60	5	9	91
0.1	65	3	3	97
0.1	75	2	2	98
0.1	85	2	2	98
0.1	95	1	1	99
0.1	120	1	1	99
0.1	130	0	0	100

Hotelling's T2 Chart

The Hotelling charting was also done to monitor the treatment process. Results in figure 5 show that the water treatment process is in control. The chart is not restricted to inter-dependent variables but normally it suits non-correlated large variables.

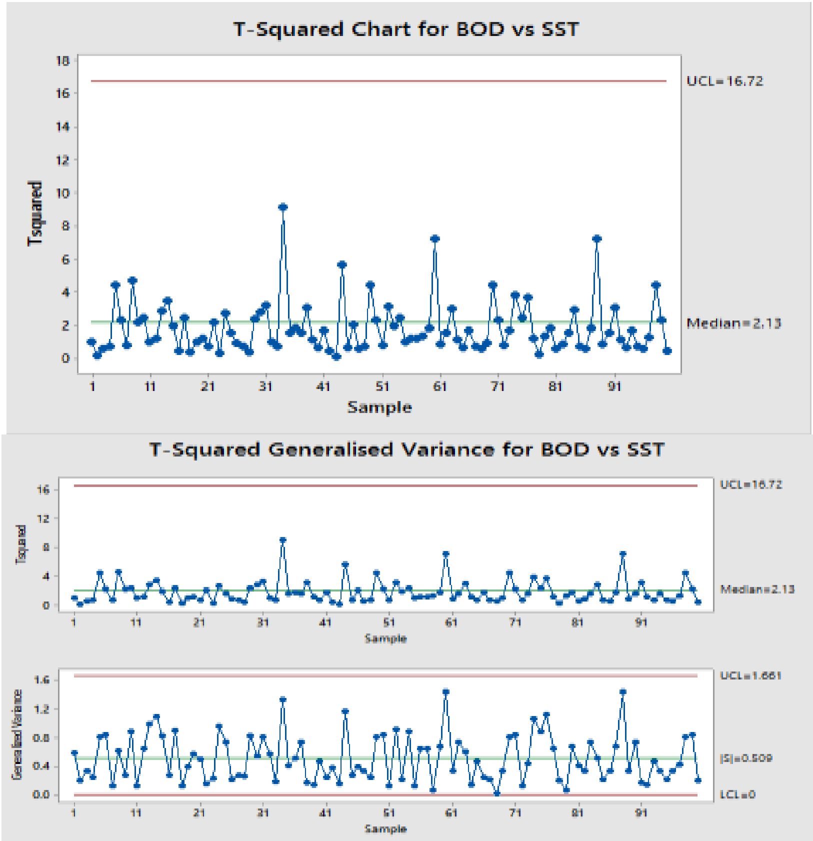

Fig-5: Hotelling t^2 charts

Control Ellipse

The Control Ellipse was constructed at 95% confidence intervals. The purpose of the control ellipse is again to monitor the water treatment process through investigating two variables (BOD and TSS). Monitoring using this technique strengthens our suspicion about the nature of the treatment process which we have already condemned in our first chart in figure 2. Results indicated in figure 6 show that the process is not in control hence needs improvement.

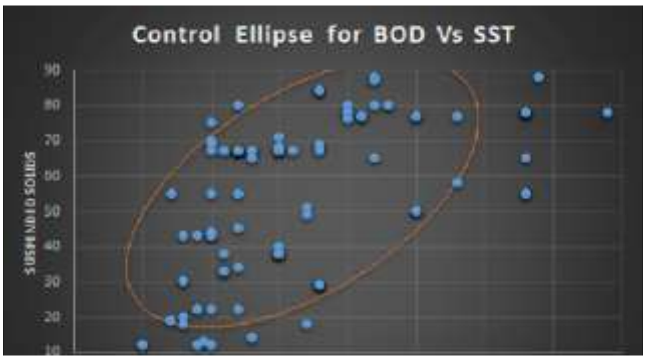

Fig-6: **Control Ellipse for BOD and TSS**

CONCLUSION

Generally, the analysis and results indicate that the process of water treatment is out of control, hence needs improvement. However, Hotelling's T^2 chart shows that the process is in control. We believe that this chart has shown a false alarm since the data present violates the independence assumptions of the Hotelling chart. In this regard, the model is therefore not fit for this type of data (dependent variables). Based on these results, we may conclude that thorough monitoring of every stage in the water treatment process is needed. On TSS, the coagulation, flocculation and sedimentation stages must be closely monitored so that the level of suspended solids in the final product of treated water is reduced. To some extent, this can be controlled since suspended solid is a physiochemical parameter infused in both physical and chemical reaction.

On the BOD, it may not be easy to determine the amount of biochemically degradable organic matter present in a water sample since the whole process is chemically oriented and water is abstracted from different sources which may be affected by different physical, chemical and environmental conditions. However, close monitoring is needed especially at chlorination stage to ensure that the required level of biochemically degradable organic matter is maintained.

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