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Evaluation on the use of turbidimetry as an indirect measurement of total suspended solids in a geothermal setting

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ABSTRACT

This study shows the correlation of turbidity and total suspended solids (TSS) in geothermal samples taken from the Leyte Geothermal Production Field. The results show that turbidity and TSS of the geothermal samples have a fair linearity with an r^2=0.5861. Using the correlation, dubbed as the final model, to calculate for TSS based on the turbidity readings, the results yielded an acceptable Mean Average Precision Error (MAPE) or 45%. The final model will be used to estimate TSS values from turbidity readings during interference monitoring to provide ample time to mitigate any interference from nearby production wells.

1. INTRODUCTION

The Leyte Geothermal Production Field has been operating for more than three decades. Drilling is used to maintain and further increase the productivity of the field as it: (a) replaces old, heavily-damaged, collapsing production and injection wells and (b) deepens some production and injection wells for enhancement. This strategy is tempered by allowing sufficient provisions and protocols so as not to damage nearby wells. Though the designs for new wells undergo a rigorous process before being accepted, there are still unforeseen responses from nearby wells. Monitoring the total suspended solids (TSS) of nearby monitor wells during drilling serves as a pre-emptive strike against further damaging wells from influx of cooler drilling fluids or cement materials. Standard gravimetric TSS analysis requires a minimum of two hours to finish. If there are successive cementing operations, the window to extract the needed data becomes narrower. Qualitative (visual) analysis also becomes limited with the rise of the use of polymers in the drilling fluids that are indiscernible to the naked eye. Thus, there is a need to look for faster analytical methods that would also give comparable data. It is then proposed to develop the use of turbidity as an indirect method to measure total suspended solids in order to provide a reliable data set within the shortest possible time. The proposal is based on several environmental studies that have established linear and log-linear relationship between TSS and turbidity.

1.1 Total suspended solids and turbidity

Total suspended solids are defined as particles that are "*less than 2 microns in diameter*" (Kemker, 2014). The standard measurement of total suspended solids is by weight using gravimetric analysis. Water samples are filtered in pre-weighed filter papers and then oven-dried for a minimum of one hour. After which, three cycles of constant weighing is performed - dry filter papers are weighed and then placed in the oven for 15 minutes before being weighed again. The results are expressed in parts per million (ppm) or milligrams per liter (mg/L).

According to the International Organization for Standardization, "*turbidity is the reduction of transparency of a liquid caused by undissolved matter"* (Lawler, 2005). Water becomes turbid due to the presence of suspended particles or colored substances (Kemker, 2014). In a geothermal setting, this would pertain to transported sediments, corrosion materials, drilling mud, cement and the solid components of drilling fluids. The suspended solid particles present in the fluid scatter light at different angles that allows for the use of turbidity in order to determine the total concentration of suspended particles (Lawler, 2005). Since turbidity is the measurement of light scatter of the particles present, it becomes affected by color from dissolved solids, temperature, shape, size and mineral composition of particles (Packman, Comings, & Booth, 1999). Given the same beam of light, particles that are smaller than the light beam scatter light in all directions in an almost symmetrical manner; while particles larger than the light beam tend to scatter light forward or further away from the source or the beam as shown in Figure 1 (Kemker, 2014). The scattering of light is also affected by the wavelength of the light source, thus the presence of colored solids in the sample will affect the turbidity reading as shorter wavelengths of light are absorbed instead of being scattered (Kemker, 2014). The colored solids observed in geothermal samples are mainly yellow sulfur-based solids brought about by the intrusion of oxygenated water from drilling fluids. The types of solids present also have an effect on the turbidity - "*mineral-based solids will reflect more light, while organic particles tend to absorb more light*" (Kemker, 2014). Geothermal samples would mostly have mineral-based particles due to transported rock sediments. The unit of measurement for turbidity is dependent on the instrument used. For this study, turbidity is expressed in nephelometric turbidity units (NTU) as a nephelometric turbidimeter is used.

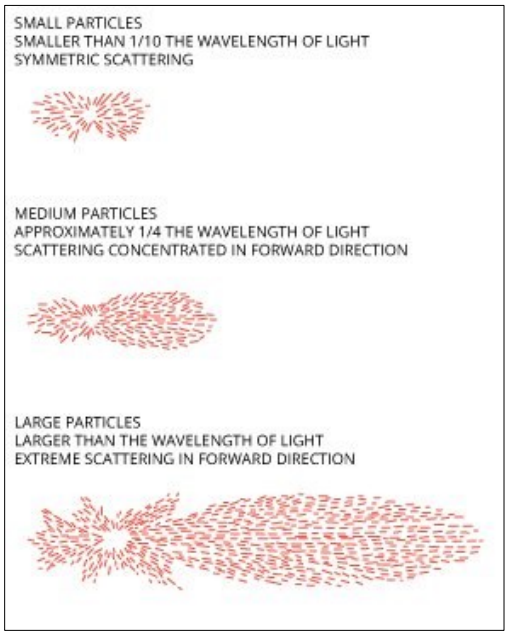


Figure 1: Light scattering based on particle sizes. (Kemker, 2014)

1.2 Nephelometric turbidimeter

Modern nephelometric turbidimeters determine the turbidity of a solution by measuring the amount of light scattered perpendicularly to an incident light beam by the particles present in a fluid sample, as shown in Figure 2 (Environmental Protection Agency, 1999). The basic parts of a turbidimeter includes: (a) a light source – preferably monochromatic so that it won't be affected by the color of the sample; (b) a sample container – usually glass cells or cuvettes; and (c) photodetectors – that detects the amount of light scattered by the particles from the incident light, which is further translated as a value of turbidity in Nephelometric Turbidity Units (NTU) (Environmental Protection Agency, 1999). This study will be using the Thermo Scientific Fischer AQ3010 turbidimeter and its accessories. It should be noted that the NTU does not contain any "*intrinsic physical, chemical or biological significance*", as any changes in the type of suspended sediment or instrument design would also change the turbidity readings; thus turbidity instruments can only be considered accurate when the conditions in which they are used are consistent (Kemker, 2014).

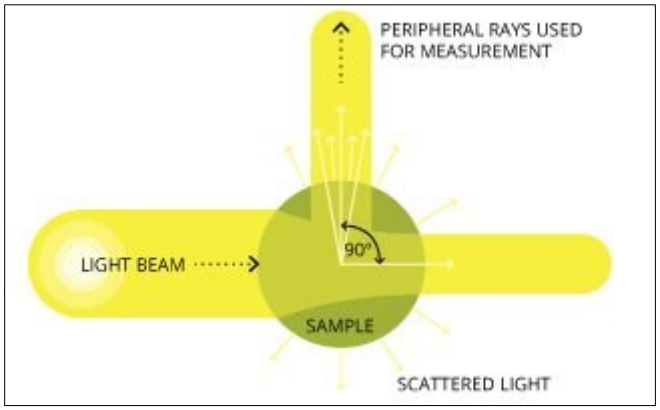


Figure 2: Nephelometry measures light scattered at 90° from the transmitted light. (Kemker, 2014)

1.3 Correlation of total suspended solids and turbidity

It has generally been observed that an increase in TSS would also increase the turbidity of the liquid. However, turbidity readings cannot be directly converted to real TSS values due to the inherent limitations of turbidity as being affected by the nature of the suspended particles that scatter light (Carlson, 2005). A 1000-ppm suspension of talcum powder will have a different turbidity reading compared to a 1000-ppm suspension of ground pepper (Carlson, 2005).

While simple direct conversion is not possible, correlating TSS and turbidity readings have been proven to be more feasible. In the absence of a standardized formula, linear regression analysis of sufficient turbidity and TSS (or suspended sediment concentration, SSC) data can provide a correlation between the two as shown in the general equations in Figure 3 (Kemker, 2014). Multiple regression models can be used if a single linear regression fails with the correlation model being validated from time to time (Kemker, 2014).

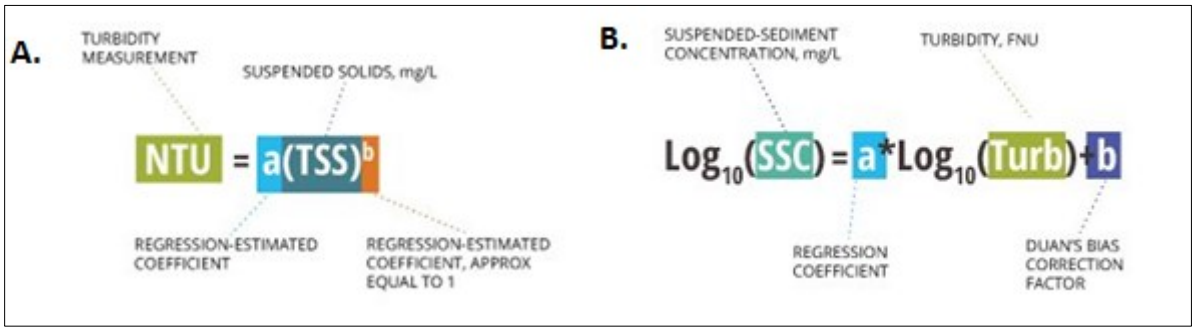


Figure 3: A. General equation for purely mineral-based sample. B. General equation for samples with organic material, air bubbles or dissolved colored materials. (Kemker, 2014)

The correlation between turbidity and TSS has been widely studied by environmental scientists in establishing surface run-off or sediment flow patterns for various water systems. Table 1 lists some of the different studies that have determined a correlation between TSS and turbidity. It has been observed that the correlations are either site-specific or season-specific. Majority of the turbidity readings in these studies were taken from inline turbidimeters, except for the study on Singapore Rivers, which utilized a table top turbidimeter. This study is a first attempt at finding a correlation between TSS and turbidity in a geothermal setting.

Table 1: Studies establishing correlations between TSS (or SSC) and turbidity

Title	Journal Reference	Results
Establishing the Relationship between turbidity and total suspended sediment concentration	CP Holliday, TC Rasmussen and WP Miller, (2003): Proceedings of the 2003 Georgia Water Resources Conference.	Linear correlation established for three different soil slurries.
Characterization of Turbidity and Total Suspended Solids in the Upper Carson River, Nevada	Richard Susfalk, Brian Fitzgerald and Anna Kurst, (2008): DHS Publication, Desert Research Institute.	Linear correlation established for four different sites.
Relationship between turbidity and total suspended solids concentration within a combined sewer system	Ali Hannouche, Chebbo Ghassan, Gwennel Ruban, et al., (2011): Water Science and Technology, IWA Publishing.	Linear correlation established for two different sites and for wet and dry weather.
Correlation between Turbidity and Total Suspended Solids in Singapore Rivers	Low Hui Xiang Daphne, Handojo Djati Utomo, Lim Zhi Hao Kenneth, (2011): Journal of Water Sustainability.	One linear correlation established for various river systems before and after rain.

2. METHODOLOGY

2.1 Synthetic and geothermal samples

Two sets of samples were prepared for this study. The first set of samples were called synthetic samples which were suspended solutions of kaolin - the primary standard of TSS analysis and drilling mud and cement - which are the primary sources of drilling interference that cause an increase in the TSS levels of monitor wells especially during cementing operations. The primary objective was to check if the log-linear relationship of turbidity and TSS determined from studies on river systems using online turbidity meters can be replicated using the AQ3010 Turbidity Meter using the synthetic samples. The secondary objective was to determine the range of the instrument. According to the manufacturer, the turbidimeter can measure a turbidity range of 0.002-800 NTU. Since the turbidity range cannot be directly translated into a TSS range, the normal range of TSS samples observed in drilling interference monitoring was used instead. The following concentrations were prepared for kaolin, mud and cement suspensions: 500ppm, 200ppm, 100ppm, 50ppm, 20ppm and 2.5ppm. The minimum limit of the TSS range is 2.5ppm, as anything below that is reported by the laboratory as <2.5ppm – the lowest detection limit set by the laboratory for the TSS analysis. Five samples were taken from each suspension, for a total of 90 ideal samples.

The second set of samples was geothermal samples taken from the monitor wells during the drilling of six wells across the production field, resulting to a total of 248 samples. This was used to evaluate the use of the turbidimeter as an indirect measurement of total suspended solids during drilling interference monitoring.

2.2 Measuring total suspended solids and turbidity

Tandem TSS and turbidity measurements were performed on all samples. For every 1-L TSS sample, 100-mL is used for turbidity measurements. TSS measurements were performed by a laboratory technician based on the Geoscientific Chemistry Laboratories Test Procedures Manual of the EDC.

The turbidimeter was calibrated at 0.02NTU, 20NTU, 100NTU and 800NTU turbidity standards specified by the manufacturer before every batch of measurements. A summary of the steps in turbidity measurement is shown in Figure 4. Turbidity samples are shaken vigorously in order to prevent solids from settling and are immediately degassed before the measurement to ensure that no suspended gases or air bubbles could affect the turbidity readings. Three successive turbidity readings were taken during each

measurement as means to check data precision. If readings are found to be erratic, the sample is re-prepared for another set of turbidity readings. The average of the three readings served as the turbidity measurement of the sample.



Figure 4: Summary of steps in turbidity measurement.

2.3 Data analysis

Simple linear regression analysis was performed on all synthetic samples. Linear regression analysis under R commander was performed on all geothermal samples under the guidance of Dr. Erniel Barrios and Dr. Joseph Ryan Lansangan of the School of Statistics from the University of the Philippines – Diliman. R commander is a Graphic User Interface developed by John Fox for the free R statistical software that provides ease in executing various statistical computations.

3. RESULTS AND DISCUSSION

3.1 Synthetic samples

Eight separate simple linear analysis regression were performed for the 90 synthetic samples. A simple linear regression and a natural log-linear regression were done for all samples and for each of the different suspensions. Simple linear regression of all samples showed fair linearity at r^2=0.88; however once the clump of 500ppm mud samples were removed from the plot, the linearity improves to an r^2=0.98 (Figure 5). Separate simple linear regression of the different suspensions show good linearity at r^2=0.994 for kaolin and mud samples; however cement samples only have a fair linearity of r^2=0.746 (Figure 6). For all simple linear regressions, two models were taken with one model assuming a y-intercept=0. Using a natural log-linear regression analysis compared with log base 10 regression yields good linearity for all samples at r^2=0.926, without the need to eliminate the 500ppm mud samples from the group and also a better linearity for the cement samples at r^2=0.814 (Figure 7). The clumping of the 500ppm mud samples may be because turbidity measurement is affected by the color of the sample. The high concentration of mud samples intensified its color which may have affected the turbidity readings. The linearity of cement samples may be because they are coarser compared to kaolin and mud; thus they settle rapidly leading to lower turbidity readings (Pavanelli & Bigi, 2005). The results of the synthetic samples yield that a better correlation can be achieved between TSS (ppm) and turbidity (NTU) using the natural logarithmic-linearregression as compared to the log base 10 regression suggested by Kemker.

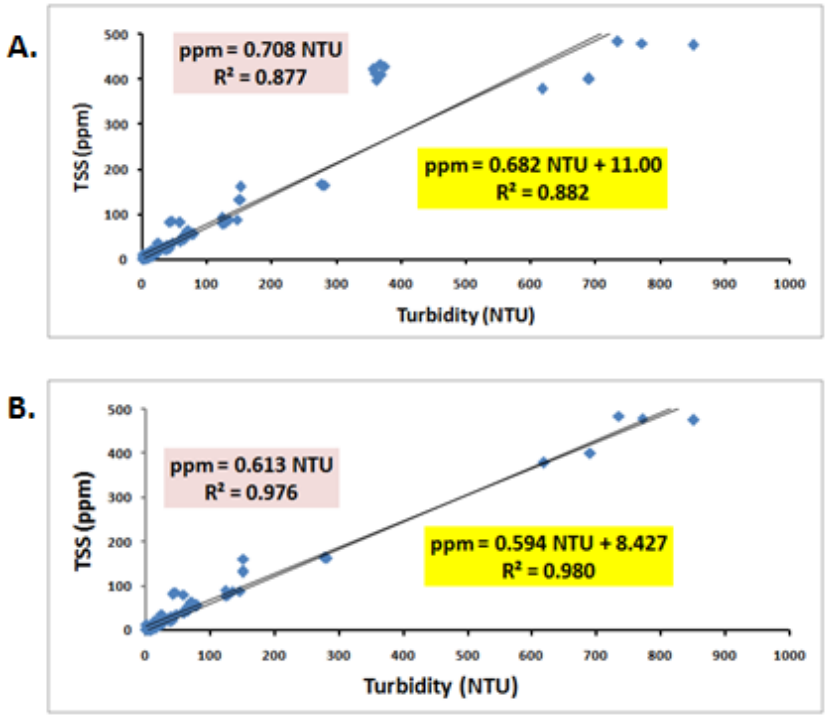


Figure 5: A. Simple linear regression of all synthetic samples. B. Simple linear regression of all synthetic samples without the 500ppm mud samples.

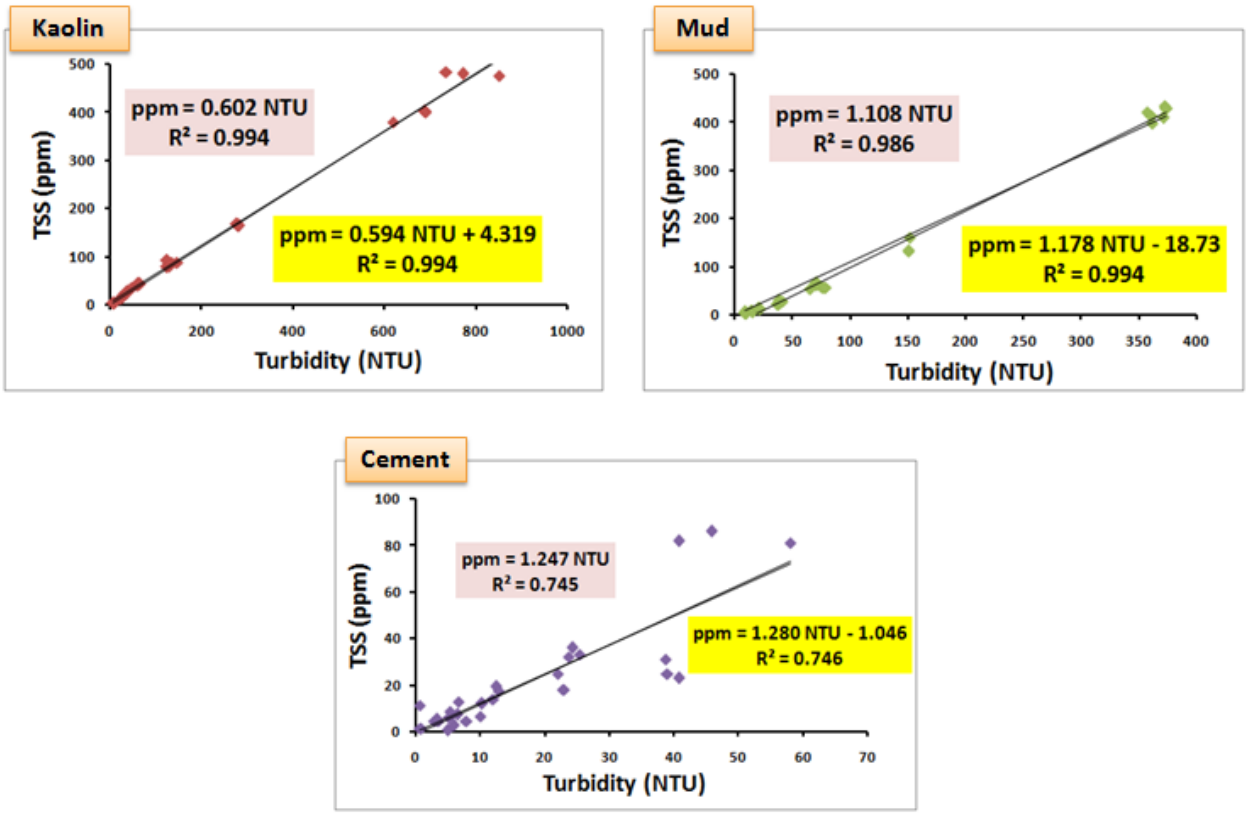


Figure 6: Simple linear analysis of kaolin, mud and cement samples.

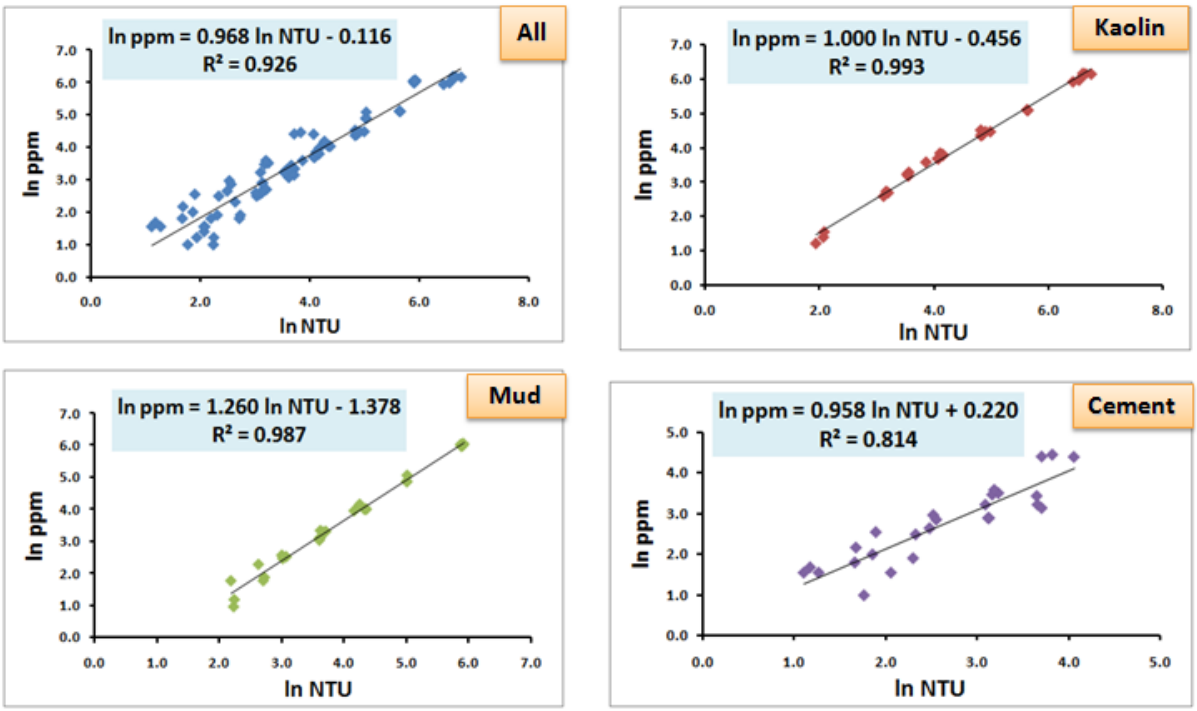


Figure 7: Natural log-linear regression analysis of kaolin, mud, cement and all samples.

3.2 Geothermal samples

Based on the promising results of the synthetic samples, the same methodology of analysis was adapted for geothermal samples. Initially, tandem turbidity and TSS measurements were only done during cementing operations of four of the six drilled wells as it was during these times when sampling was intensive (hourly), compared to the 3x/week sampling conducted during regular drilling activities. However, in order to further establish if turbidity can be used for drilling interference monitoring, tandem turbidity and TSS measurements were done throughout the interference monitoring during the drilling of the other two wells. It was observed that there were two types of geothermal TSS samples - colorless and yellowish samples. The yellow color of the samples maybe due to sulfur-based solids that were produced upon the intrusion of oxygenated drilling fluids into the neighboring wells. The yellowish samples tend to have higher turbidity readings compared to the colorless samples that have almost the same TSS levels. This observation may be different from the study of Gippel which notes that water color decreases nephelometric turbidity (Gippel, 1995).

Initial simple linear regression and natural-log liner regression were done for all samples but yielded low linearity, thus it was done separately for both colorless and yellowish samples (Figures 8 and 9). It was observed that the natural log-linear regression plots yielded a higher linearity compared to the simple linear regression plots. The equations in these natural log-linear regression plots were now used to calculate for TSS and compared these calculated TSS values to the real values given by the laboratory. The results shown in Figure 10, show that calculated TSS values from equations result to a overestimation for samples with low TSS values and underestimation of high TSS values. Calculated Mean Absolute Percent Error (MAPE) for colorless geothermal samples is 384%, while for yellowish geothermal samples was 904%.

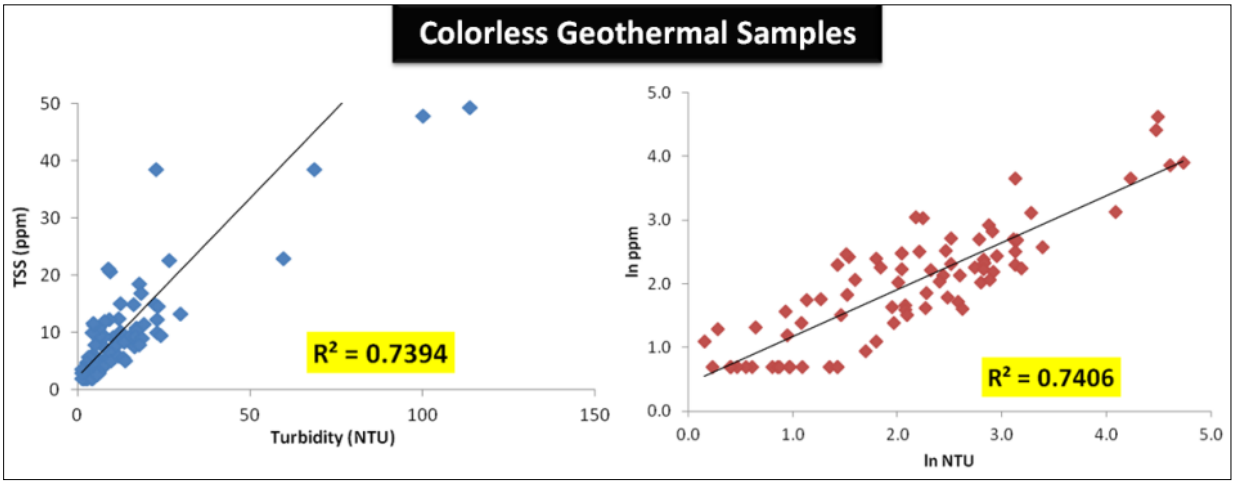


Figure 8: Simple linear regression and natural log-linear relationship of colorless geothermal samples.

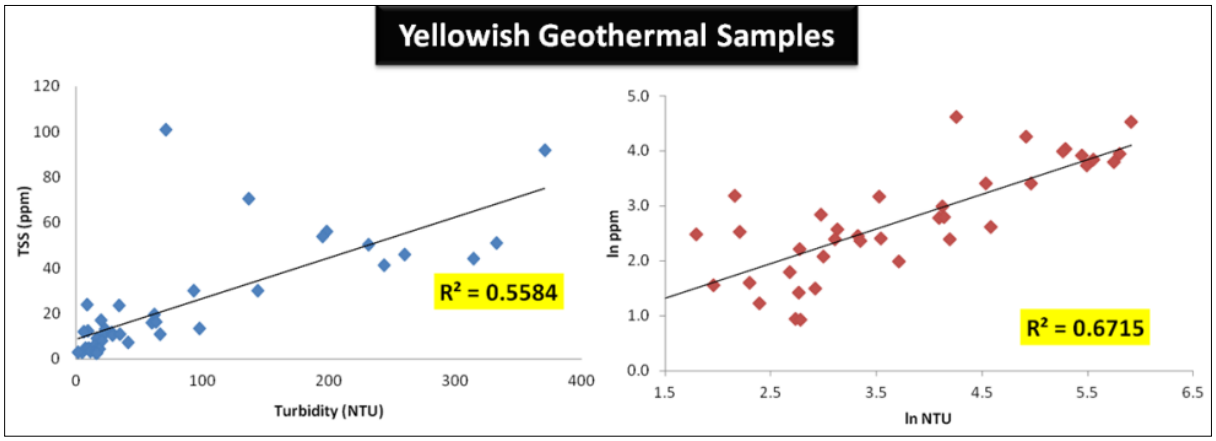


Figure 9: Simple linear regression and natural log-linear relationship of yellowish geothermal samples.

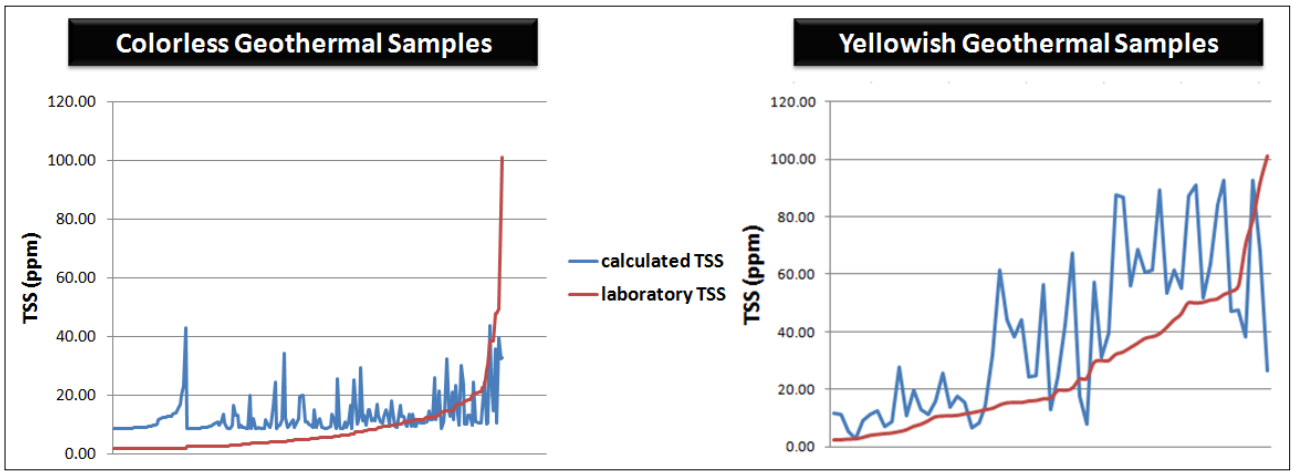


Figure 10: Comparison of calculated TSS and laboratory TSS using the natural-log linear equations from the colorless and yellowish geothermal samples, with MAPE at 384% and 904% respectively.

In order to create a better correlation model from the experimental data, linear regression was done using R commander software. Through the R commander software, other variables that may affect the TSS or turbidity of the sample were included (Table 2). Also, instead of separating colorless from yellowish samples, the color of the sample was included as a dummy variable. Interactions between the different variables were also considered during the regression analysis. %WF is calculated as a ratio of the Water Flow (kg/s) against the Total Mass Flow (kg/s) in a production well.

Table 2: Other variables included in making the correlation model for TSS and turbidity.

Variable	Unit
Enthalpy (H) of production well	kJ/kg
%Water Flow (%WF) of production well	Ratio, no unit
Sector of production well	Considered as dummy variable
Color of samples	Considered as dummy variable

After several regression analyses, only color and %WF were the significant variables, aside from TSS and turbidity, that would be included in the Final Model. The Final Model yielded a fair linearity of r^2=0.5861. The Final Model includes color as a dummy variable, and when used in calculations: colorless samples will have color=0 and yellowish samples will have color=1 (Figure 11). When used to calculate TSS and compared against laboratory TSS values, low TSS values were not overestimated, though high TSS values are slightly underestimated (Figure 12). However, its calculated MAPE is only 45%, which is far more acceptable that the previous natural log-linear regression equations for the colorless and yellowish geothermal samples.

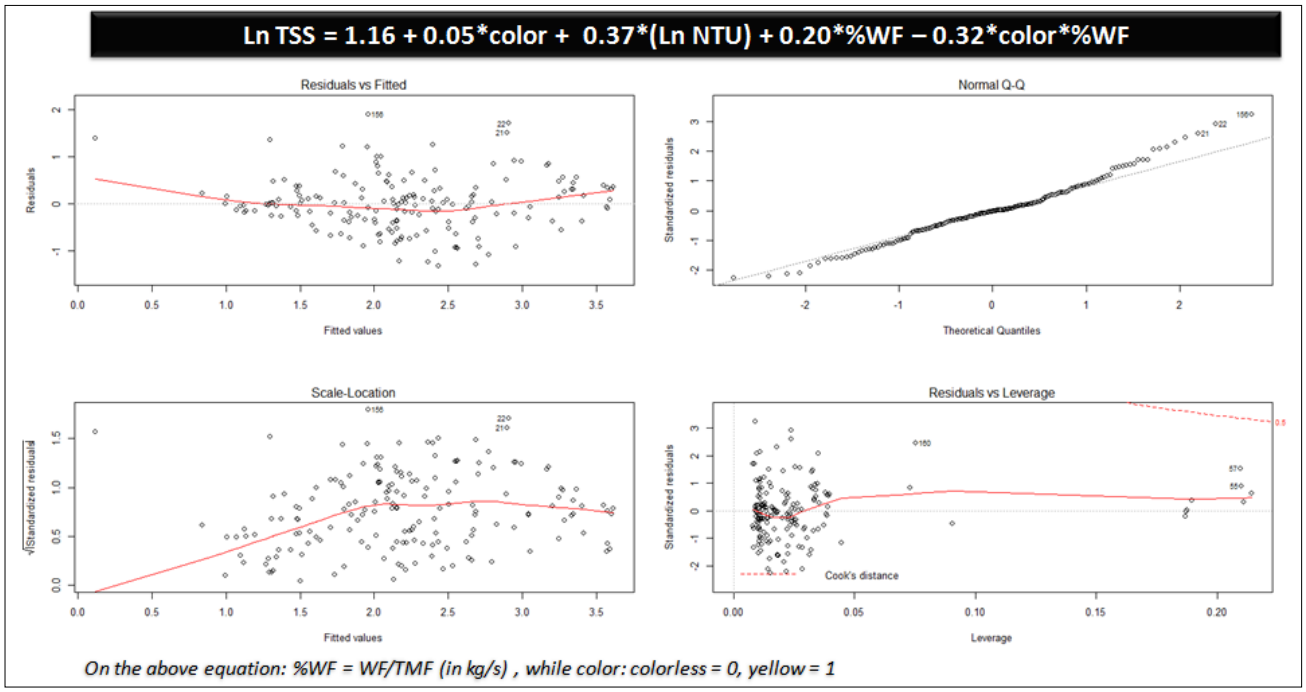


Figure 11: Basic diagnostic plots of the Final Model using R commander.

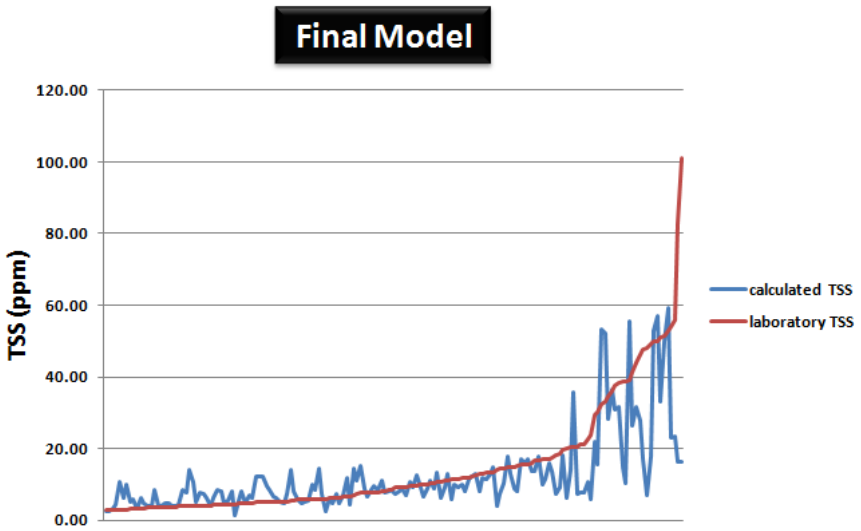


Figure 12: Comparison of calculated TSS and laboratory TSS using the Final Model with MAPE of 45%.

While the final model was able to achieve a better correlation model for turbidity and TSS, it was only able to capture some and not all of the measureable variables that affect the correlation between turbidity and TSS. Some of these variables may be the types of minerals present in the geothermal samples as these can also affect turbidity measurements due to "*variations in color, shape, size density, fluorescence and refractive index*" (Gippel, 1995). There is also the presence of cement particles that easily settle and can affect turbidity measurements. However, even with these limitations, the final model can still be used as a rough estimate of the TSS and serve as an early warning that nearby production wells are responding to drilling interference. Total analysis time for turbidity measurements is only 5-10 minutes (with the latter including calibration time) compared to the 2-2.5 hour wait for TSS results. Thus, the turbidity results would provide a wider window for mitigating drilling interference, especially during successive cementing operations. Gravimetric analysis would still remain as a standard source of TSS data to validate the calculated TSS data from the Final Model.

4. CONCLUSION

The study was able to find a reasonable correlation between turbidity and total suspended solids from geothermal samples. Calculated TSS values from the Final Model can serve as early warning indicators of interference in nearby wells, considering that turbidity measurements require a shorter time of analysis compared to standard TSS analysis. However, TSS results from gravimetric analysis are still needed for validation and will still serve as the official data.

Further improvements in the study would be to determine another separate equation that would calculate the uncertainty of the calculated TSS value from the Final Model as presented in a study by Bertrand-Krajewski in 2004.

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