Journal of Engineering, Sciences, Assiut University, Vol. 35, No. 6, pp. 1541-1558, November 2007

A METHODOLOGY TO DETERMINE THE OPTIMUM SAMPLING FREQUENCY FOR CONTINUOUS WATER QUALITY PARAMETERS

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(Received September 23, 2007 Accepted October 21, 2007)

This paper presents a methodology for determining the optimum sampling frequency using long-term monitoring data, with a high sampling frequency, from a real field case in an industrial site. The initial data used in the development of the methodology using Fast Fourier Transformer (FFT) was obtained from an already established continuous surface water monitoring location for conductivity variable. The methodology was later applied to the laboratory test data of different Reference TUBERs provided by two industrial companies. The suggested methodology aims at providing a guideline for the suitable sampling frequency for some water quality parameters such as: (temperature, pH, electrical conductivity, dissolved oxygen, nitrate, and chloride, as they are being monitored around mining and landfill sites. Results showed that the current sampling interval could be increased by 4 times for some parameters and more for others without much change in the main information recorded in the final output signal.

KEYWORDS: *Sampling frequency, water quality parameters, FTT, power spectrum density.*

1. INTRODUCTION AND OBJECTIVE

There are several methods available for determining the common water quality parameters like temperature, pH, electrical conductivity, alkalinity, chloride, nitrate, and dissolved oxygen. While being accurate and precise, these procedures are time consuming and thereby expensive when analysing large sample sets for routine monitoring [1]. An alternative approach to assist in monitoring these parameters is to determine their optimum sampling frequency.

On the other hand, monitoring the water quality parameters became an important issue due to the ascending concern of the public and government to have standard and healthy water.

The main problem for conducting a continuous monitoring of water quality data is the high cost especially if the parameters to be detected are too many as the case around mines and landfills [2].

It should be mentioned that several research investigated other factors that might affect the selection of the sampling intervals of water quality parameters monitoring such as the groundwater velocity: Hudak (2001) evaluated how groundwater velocity affects the sampling interval of a groundwater monitoring network and its ability to intercept contaminant plumes before reaching a buffer zone boundary using a computer simulation model [3]. Loftis and Ward (1980) introduced methods for predicting confidence interval widths at specified sampling frequencies; they have considered both seasonal variation and serial correlation of the quality time series [4].

However, the aim of this paper is to define, through monitored data analysis, the optimum sampling frequency from economical and scientific point of view that applies to the groundwater quality parameters in mines and landfill sites. Such methodology will assist the industry in saving time and money. The methodology was developed based on the analysis of real data provided from the industry for a conductivity parameter.

2. SAMPLING FREQUENCY ANALYSIS METHODOLOGY

As far as groundwater-sampling frequency is concerned, the current practice in industry is usually based upon the extent of the historical data available before a project starts. The specifications used are very general and, in the main, involve periodic sampling (grab sampling). To develop the methodology, it was believed that a reasonably long-term monitoring data, with a high sampling frequency, from a real field case in an industrial site is essential to approve the capability of the suggested methodology. The initial data used in the development of the methodology therefore was obtained from an already established continuous surface water monitoring location for conductivity data. The methodology and the initial data analysis are reported in the next section.

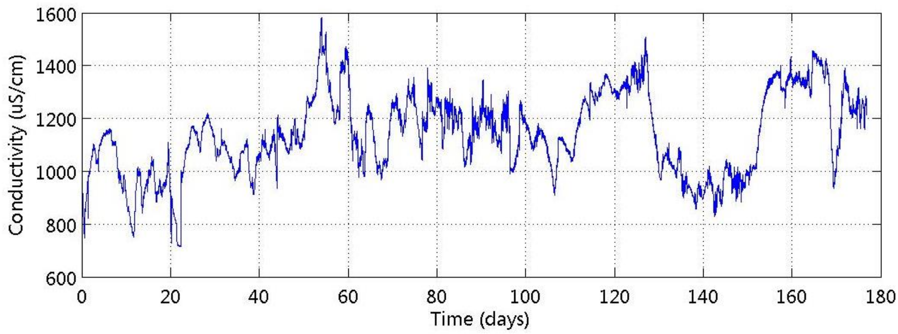
The main objective of this research is to identify the noise and filter the signal in order to determine the optimum sampling frequency for the groundwater parameters in the mining and landfill environment. The initial data used for the development of the methodology covers a period of six months with a 15 minutes interval of conductivity monitoring. The continuously monitored data is first plotted as a time series graph to examine the continuity and trend of the measured variable. The signal is analysed using the Fourier analysis techniques to study the frequency components of different sampling frequency components. For this purpose, FFT (Fast Fourier Transform) and PSD (Power Spectrum Density) are used to determine the optimum sampling frequency and the power of the signal.

Theoretically, the minimum sampling frequency must be $2f_{max}$. (Where f_{max}. is the maximum frequency component in the original signal) [5]. However, in practice, this is usually taken as $4f_{max}$. A suitable filter was designed to pass the main components of the signal and cut off the minor ones (noise). It has been assumed that the noise in the signal would not exceed 10% of the original power of the signal;

otherwise, we assume that the noise is due to sensor failure or draft. A macro was written in MATLAB [6] to carry out the analysis. The procedure finalised is summarised below:

1. *Time series plot:* After the initial analysis of the raw data using simple statistical tools, the raw data is plotted in time domain to observe the change in the parameter concerned in time, **Figure 1a**.
2. *Removing the mean and the trend:* In order that the change in the variable with time is analysed effectively, the mean of the data is removed first. If the recorded data has a trend, it is important that the trend is also removed.

Removing both the mean and the trend does not affect the information in the signal. **Figure 1b** illustrates the continuously monitored conductivity data after removing both the mean and the trend.



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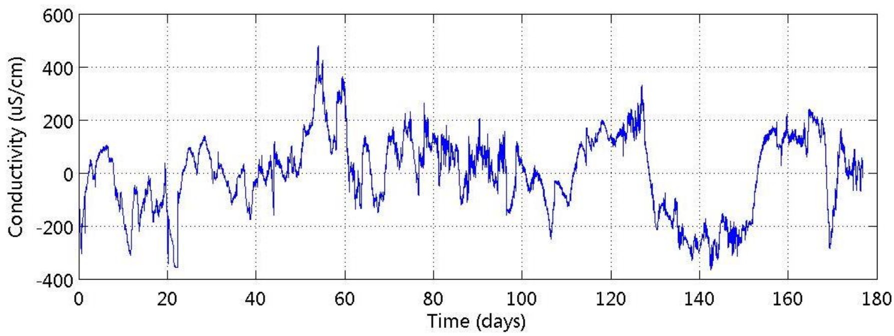

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Figure 1: Frequency analysis of electrical conductivity data a) original data; b) after mean and trend is removed from the signal.

3. *FFT (Fast Fourier Transform):* A traditional method of spectral estimation is the Fourier analysis, which can be used to define spectral peaks in time records [7]. Fast Fourier Transform (FFT) is used to convert the data from the time domain to the frequency domain where the components of the signal could be identified easily (**Figure 2**). The complicated form of the observed data can be represented

by an aggregate of simple wave forms that are expressed by the amplitude of the cosine and sine terms, a_n and b_n, respectively:

The simplest relation between a finite-length sequence *x[n]*, defined for $0 \le n \ge N-1$, and its discrete-time Fourier transform DTFT $X(e^{j\omega})$ is obtained by uniformly sampling $X(e^{j\omega})$ on the ω-axis between $0 \le \omega \ge 2\pi$ at $\omega_k = 2\pi k / N$, k = 0,1, N-1. [8].

$$X[k] = X(e^{j\omega}) \,\Big|_{\omega = 2\pi k/N} = \sum_{n=0}^{N-1} x[n] e^{-2j\pi kn/N} \qquad k = 0, 1, ., N\text{-}1 \tag{1}$$

Where:

X[k] is a finite length sequence in the frequency domain and is of length *N*. The sequence *X[k*] is called the Discrete Fourier Transformer (DFT) of the sequence *x[n]*.

Using the commonly used notation

$$W_N = e^{-j2\pi/N} \tag{2}$$

Equation (1) can be rewritten as:

$$X[k] = \sum_{n=0}^{N-1} x[n] W_N^{kn} \qquad k = 0, 1, \ldots, N\text{-}1. \tag{3}$$

4. *Signal filtering:* Here the objective is to remove the noise without losing a significant portion of the signal. Once the FFT has been applied to the time series data, one can select a suitable filter (high pass or low pass filter) for refining the signal from its useless components (noise). The FFT shows the principal components of the signal. In some applications, the first two main components could be sufficient to represent the main information in the signal. After the FFT, the original signal is filtered using the cut-off frequency (*fc*):

$$B = fir1\left(D, \frac{2\,fc}{fs1}\right) \tag{4}$$

Where:

fc = cut-off frequency

fs_1 = original sampling frequency (1/(15*60)) = 0.0011 (in the case discussed here)

*fir*1 = is an M-file implementation of MATLAB Programs for Digital Signal Processing [6].

D = filter degree, (30-40) say 35.

In selecting the correct cut-off frequency (*fc*), thus the optimum sampling frequency from the processed signal, Power Spectrum Density (PSD) analysis is used.

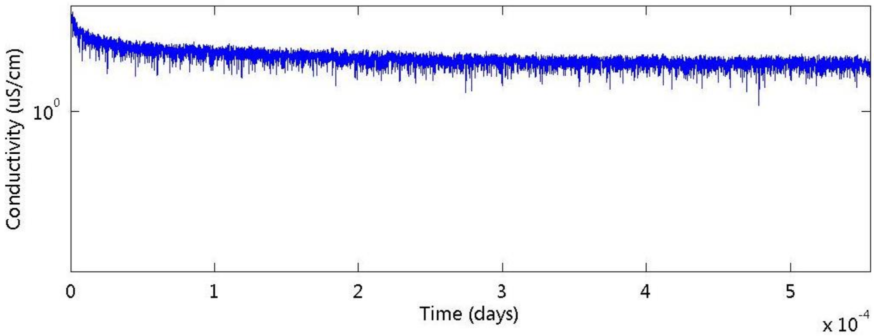
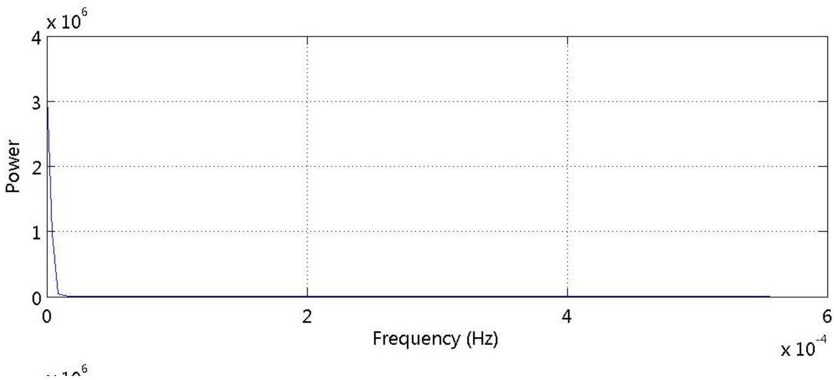


Figure 2: Fast Fourier Transform of the electrical conductivity data after mean and trend is removed from the signal.

After FFT application to the original signal (**Figure 2**), a cut-off frequency is selected through the analysis of the signal components. Assuming that the maximum information in the signal is within 90% of its original power (the rest is noise), PSD is used to assess the validity of the cut-off frequency selected. This is an iterative process where the selected cut-off frequency (*fc*) is used to filter the original signal., then the PSD of the signal after filtering is compared with the PSD of the original signal (**Figures 3a** and **b**) until it converges to:

$$PSD_{\text{filtered signal}} \geq 90\% \; PSD_{\text{original signal}}$$

by reducing the cut-off frequency at each step. Table 1 illustrates the change of cut-off frequency (fc), the related PSD ratio and the resultant sampling interval during the iterative steps conducted for a conductivity monitoring signal. Once the final cut-off frequency (fc) is decided upon, the original signal is filtered (Figure 4b) to remove the noise and the optimum sampling frequency calculated.



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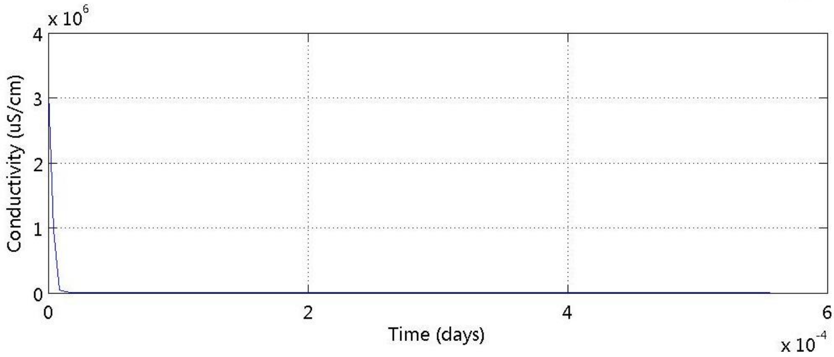


(b)

Figure 3: Power density spectrum of the electrical conductivity data a) original signal; b) after the removal of trend and noise.

Table 1: Change of cut-off frequency (*fc*), the PSD ratio and the resultant-sampling interval for a continuous conductivity monitoring data.

Variable	Cut-off Frequency (Hz)	PSD of the Original Signal	PSD of the Filtered Signal	$PSD_{filtered}$ / $PSD_{original}$ (%)	Sampling Interval (hr)
Conductivity	5.4E-04	3.5507E+08	3.5505E+08	99.99	
	1.0E-04	3.5507E+08	3.5397E+08	99.69	0.6944
	8.0E-05	3.5507E+08	3.5647E+08	99.60	0.8681
	5.0E-05	3.5507E+08	3.5217E+08	99.18	1.3889
	1.0E-05	3.5507E+08	3.4983E+08	98.53	6.9444
	5.0E-06	3.5507E+08	3.4975E+08	98.50	**13.4775**
	5.0E-07	3.5507E+08	3.4975E+08	98.50	138.889

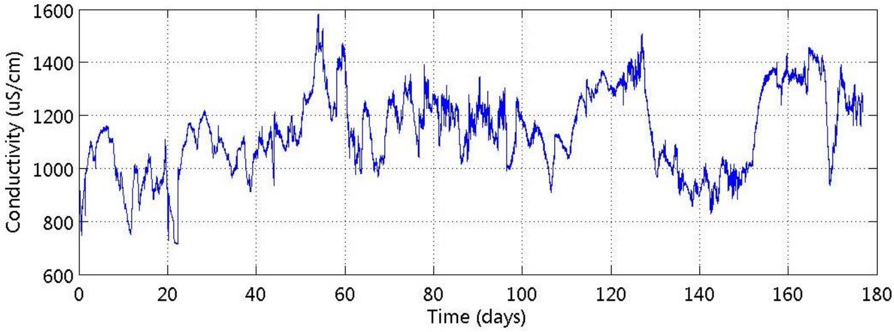
For the first iteration:
The actual sampling frequency (fs) =1/T (actual sampling time in seconds), i.e.,

$f = 1/(15*60)$

$fs = 2\ fmax \quad \Rightarrow \quad 1/(15*60) = 2\ fmax$

Select $fc = fmax \quad \Rightarrow \quad fc = 5.5E\text{-}04$ (Hz).

Once the PSD converges to the required level, the optimum sampling frequency is calculated from the related cut-off frequency as: $f_{optimum} = 4fc$.



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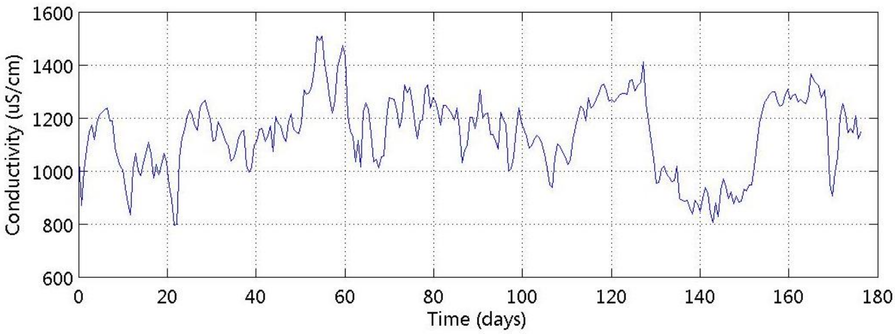


(b)

Figure 4: Comparison of electrical conductivity data a) original data; b) resulting signal after the trend and noise are removed based on correct *fc*.

3. VALIDATION OF SAMPLING FREQUENCY METHODOLOGY

In order to validate the methodology described above, water quality monitoring data from the laboratory trials of two Reference TUBERs were used. Data was collected from two case studies (a mine site and a landfill site) [9]. In order to help identify a maximum representative frequency, these data were obtained at intervals as small as possible considering the length of time over which the data acquisition was to proceed (the shorter the time interval, the greater the battery consumption).

At the landfill site, 10 minutes sampling intervals were used, to monitor several water quality parameters. At the mine site, the monitoring frequency was 15 minutes with weekly analysis of data throughout. This data was used to further evaluate the methodology developed and to assess the sampling frequency for parameters such as pH, dissolved oxygen, conductivity, temperature, chloride, ammonium, nitrate, pressure (level) and redox potential. The results of these validation studies are given in the next sections.

3.1 Analysis of Sampling Period and Sensor Type

In order to test the reliability of the methodology, the suggested methodology was used to examine the current sampling frequency of two TUBERs, "I and II". The data were collected over 10 weeks and data analysed in weekly blocks as well as for the complete 10 weeks period [10]. Later, the data for the two TUBERs was evaluated for optimum sampling frequency for each individual sensor over the whole monitoring period and comparisons made. In all cases, the sampling interval for the measurements was 15 minutes.

The sampling frequency procedure described before was applied to this data, treating the signal in weekly intervals as well as the whole monitoring period, for all the sensors that functioned. The results are given in **Tables 2 and 3.**

Figure 5 presents the frequency analysis and signal filtering results for the dissolved oxygen sensor (as an example) for a particular week.

Table 2: Sampling frequency analysis results for Reference TUBER "I", sampling interval = 15 minutes.

Variable	Cut-off Frequency (Hz)	PSD of the Original Signal	PSD of the Filtered Signal	$PSD_{filtered}$ / $PSD_{original}$ (%)	Optimum Sampling Interval (hr)
Temperature	3.00E-05	18886	18586	98.57	2.315
Conductivity	1.00E-05	6.5912E +05	6.4959E +05	98.55	6.944
pH	4.00E-05	326.2021	317.1197	97.22	1.736
Redox	5.00E-05	1.4410E+06	1.3001E+06	90.23	1.389
Dissolved O_2	3.50E-05	1.3939E+03	1.3730E+03	98.50	2.315

- Number of observations = 6029

Table 3: Sampling frequency analysis results for Reference TUBER "II", sampling interval = 15 minutes.

Variable	Cut-off Frequency (Hz)	PSD of the Original Signal	PSD of the Filtered Signal	$PSD_{filtered}$ / $PSD_{original}$ (%)	Optimum Sampling Interval (hr)
Temperature	2.00E-05	18496	18201	98.42	3.472
Conductivity	2.00E-05	3.5914E+05	3.5650E+05	99.26	6.944
pH	4.00E-05	169.3844	165.4940	97.70	3.472
Chloride	2.00E-05	7.8606E+09	7.8191E+09	99.47	3.472
Dissolved O_2	6.00E-05	1.0300E+03	985.6579	97.30	2.315

- Number of observations = 6034

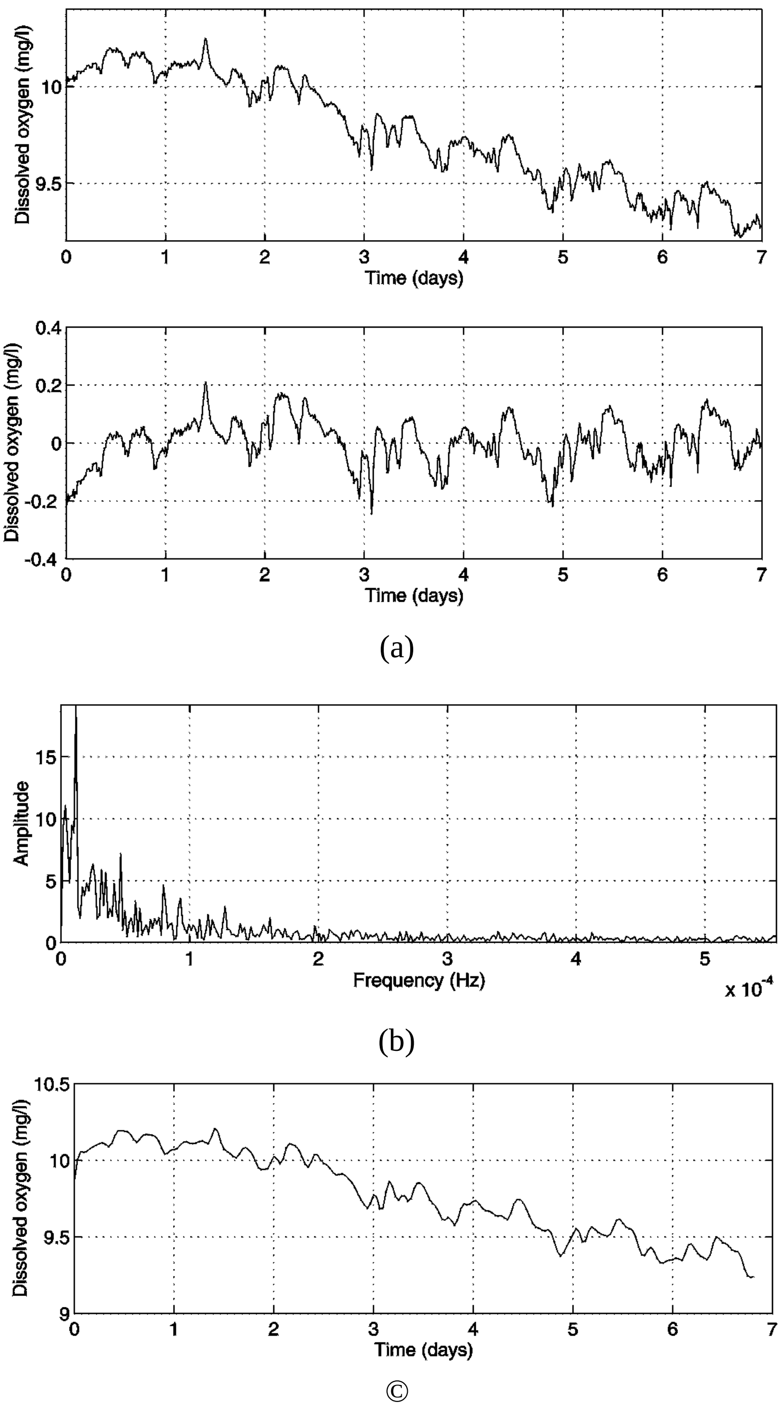


Figure 5: Frequency analysis of dissolved oxygen measurements every 15 minutes from Reference TUBER "I" for one week (a) original data and after the removal of the mean and trend; (b) Fast Fourier Transform of dissolved oxygen measurements after mean and trend is removed; (c) resulting data after the removal of the trend and noise from the signal.

3.2 Application of Sampling Frequency Methodology around a Mine Site

The reference TUBER "I", that has been tested and introduced in the previous section, was installed in the field in a monitoring well, near tailings pond very close to a mine site. The TUBER acquired data at 15 minute intervals for the entire monitoring period. Water quality data were monitored regularly in order to assess the behaviour of the sensors for about 3.5 months (10500 samples). The continuous monitoring data were compiled and analysed using the developed sampling frequency methodology.

The objective of this application is to determine the optimum sampling frequency and, decide whether a modification for the entire sampling interval is required or not. Therefore, the results would reveal the capability of the method to assess the sampling frequency for parameters such as pH, and electrical conductivity. **Table 4** presents the results of statistical analysis of the monitoring data.

Table 4: Statistical analysis results for the parameters measured using TUBER "I".

Statistical Parameters	Level m	Temp. ^{0}C	Conductivity µS/cm@25C^0	pH units	Redox mV	Dissolved O_2 mg/l
Mean	4.888	10.610	1716.952	7.925	276.981	0.088
Standard Deviation	0.129	0.278	78.955	1.220	26.318	0.031
Range	0.578	0.970	387.680	3.950	133.540	0.190
Maximum	4.999	11.050	1876.780	10.310	322.210	0.220
Count	10500	10500	10500	10500	10500	10500
Confidence Level (95.0%)	0.002	0.005	1.510	0.023	0.503	0.001

- Device started: 22/07/1998 13:00 till 8/11/1998 21:45 with sampling interval = 15 minutes.

Figure 6 illustrates pH sensor, as an example, field data for TUBER "I".

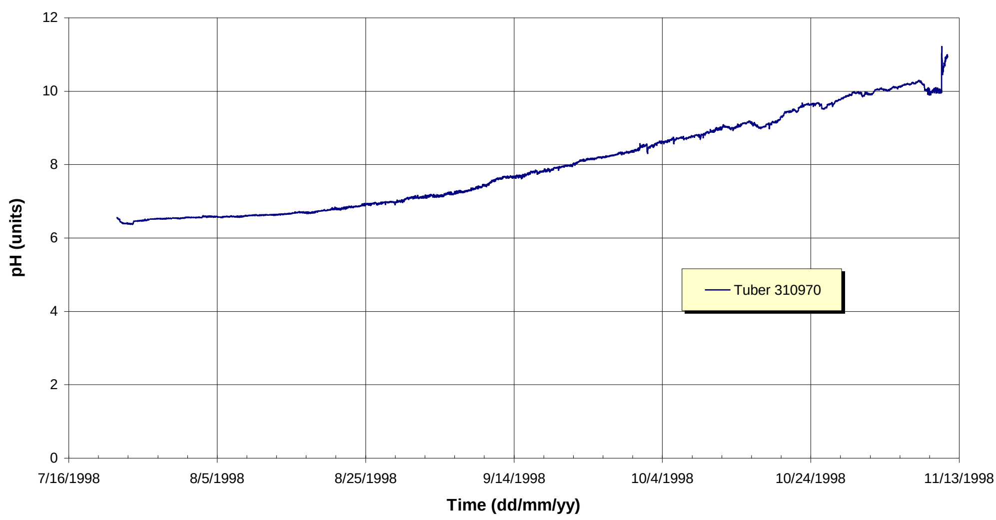


Figure 6: pH measurements in the groundwater well near a mine site.

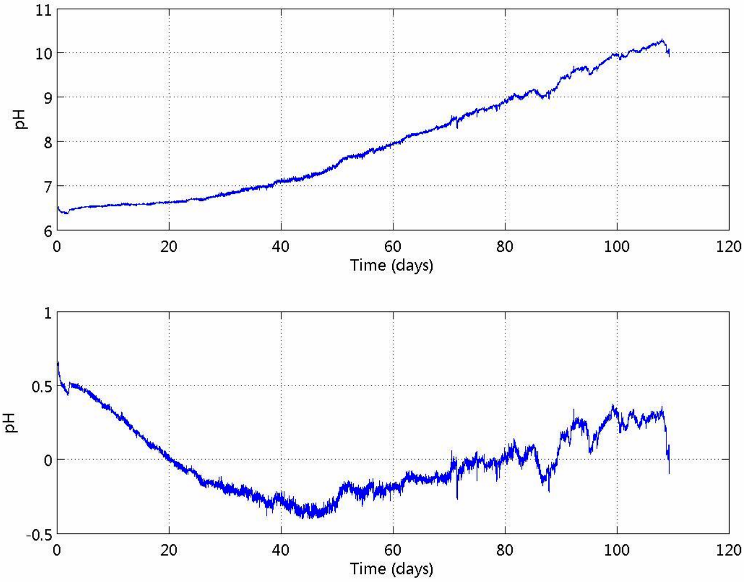
The sampling frequency analysis procedure described earlier was applied to this data, treating the signal for the whole monitoring period, for all the sensors that functioned. **Table 5** presents the results of this analysis for TUBER "I". **Figure 7** illustrates these results for the pH sensor for TUBER "I".

Table 5: Sampling frequency analysis results for Reference TUBER "I", sampling interval = 15 minutes.

Variable	Cut-off Frequency (Hz)	PSD of the Original Signal	PSD of the Filtered Signal	$PSD_{filtered}$ / $PSD_{original}$ (%)	Optimum Sampling Interval (hr)
Temperature	5.00E-06	563.7892	559.7206	99.28	13.889
Conductivity	5.00E-06	3.91E+07	3.87E+07	99.14	13.889
pH	5.00E-06	593.8711	588.2878	99.06	13.889
Redox	4.00E-05	2.61E+06	2.37E+06	90.83	1.7361
Dissolved O_2	5.20E-04	9.1518	8.4157	91.96	0.3135

* Number of observations = 10500

The above results reveal that the temperature, conductivity and pH sensors worked consistently for the length of the monitoring period downhole. As a result, the optimum sampling frequency determined by the FFT analysis was more than 13 hours. This reflects to a high signal over noise ratio, that is a very important aspect of the function of the sensors. However this does not mean that it is possible to predict/model the in-between values if samples were collected every 13 hours. On the other hand both the Redox and dissolved oxygen sensors were shown to have much lower optimum frequency values (1.7361 and 0.1335 hrs), which translates to a low signal over noise ratio, even though the measurements could be within acceptable ranges.



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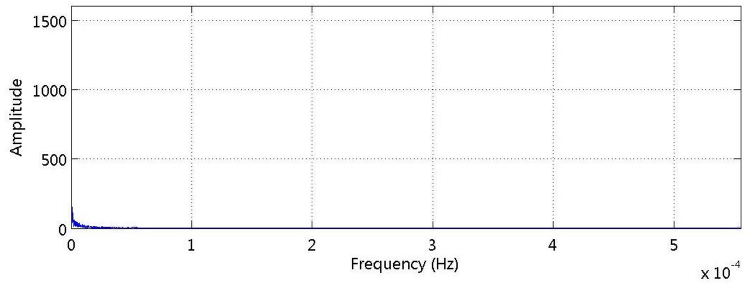

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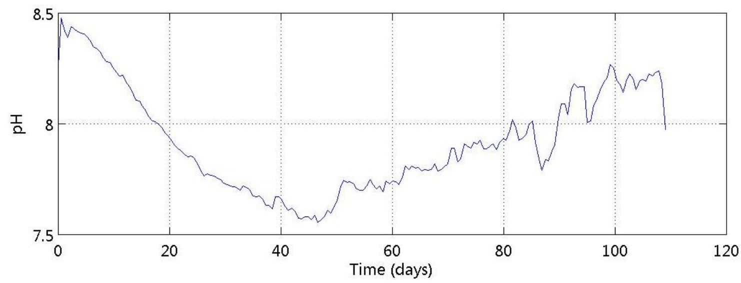


(c)

Figure 7: Frequency analysis of pH measurements every 15 minutes from Reference TUBER "I" at a mine site (a) original data and after the removal of the mean and trend; (b) Fast Fourier Transform of pH measurements after mean and trend is removed; (c) resulting data after the removal of the trend and noise from the signal.

3.3 Application of Sampling Frequency Methodology around a Landfill

Similar analysis of sampling data from the field was carried out using TUBERs "1 and 2" in groundwater wells (S6 and S7) at a Northern Italian landfill site (data provided by Ismes S.p.A.) [11], to evaluate the sample data and optimum sampling frequency assessment. Sampling intervals of 20, 30 and 40 minutes were used with these sensors. **Figure 8** illustrates the original monitoring data obtained for electrical conductivity in the field. **Table 6** shows the operational conditions of the two reference TUBERs as they used in the field.

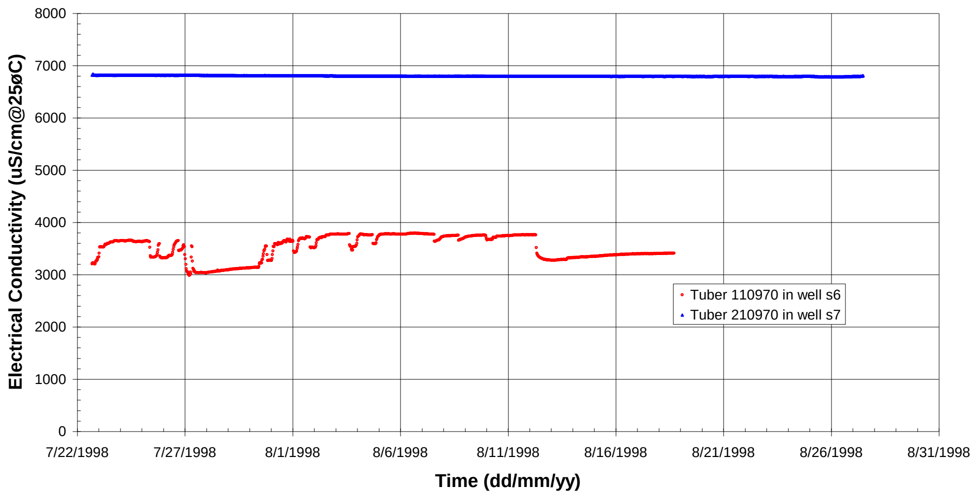


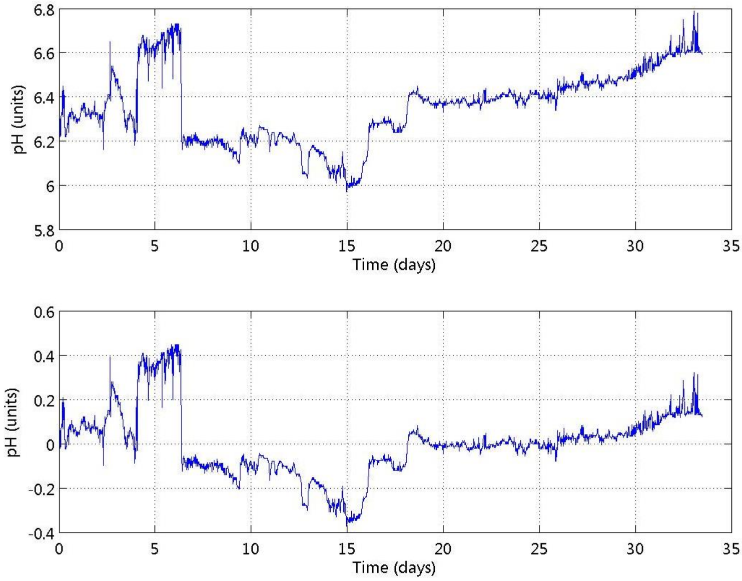
Figure 8: Electrical conductivity measurements for TUBERs "1 and 2" in the field.

The FFT analysis of all the test data for all the sensors that functioned were carried out. The results of these analyses, using a sampling frequency of 20 and 40 minutes, are presented in **Tables 7 and 8**, while **Table 9** shows the results obtained from using TUBER "1" at well "S6" with initial sampling frequency of 40 minutes.

Figures 9 and 10 illustrate the FFT analysis of the pH and electrical conductivity signal for 20, and 30 minute sampling interval respectively.

Table 6: Operational sampling frequency for the TUBERs "1 and 2" at the Northern Italian landfill**.**

Reference TUBER	Well	Started	Until	Sampling interval	No of observations
1	S6	18/06/1998 13:12	22/07/1998 00:52	20 min.	2412
		22/07/1998 14:08	27/08/1998 01:52	40 min.	1283
2	S7	17/06/1998 13:12	22/07/1998 15:12	40 min.	1224
		22/07/1998 16:30	27/08/1998 00:00	30 min.	1696



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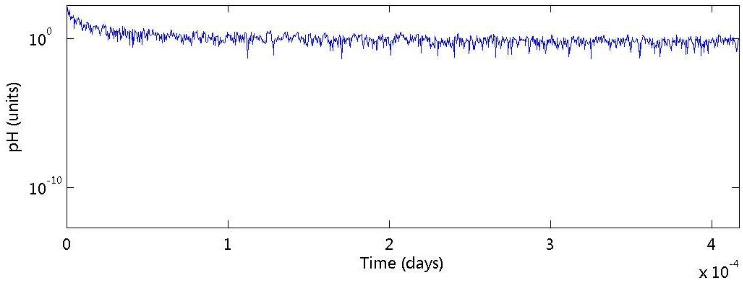

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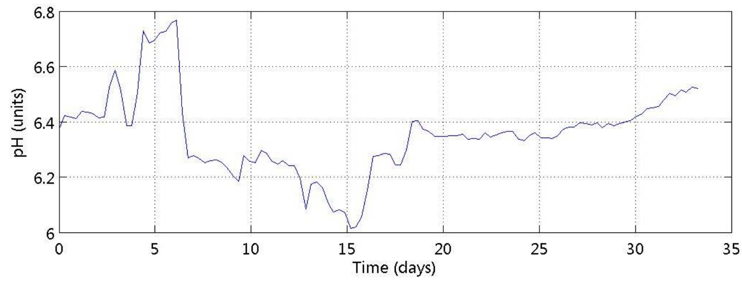

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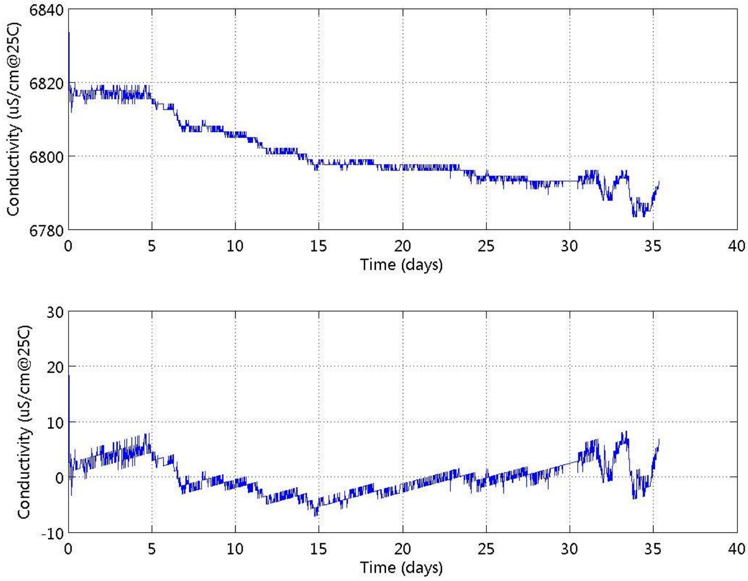
Figure 9: Frequency analysis of pH measurements every 20 minutes from Reference TUBER "1" (a) original data and after the removal of the mean and trend; (b) Fast Fourier Transform of conductivity measurements after mean and trend is removed; (c) resulting data after the removal of the trend and noise from the signal.



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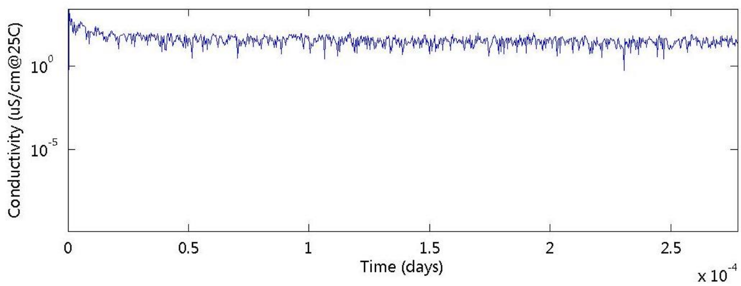

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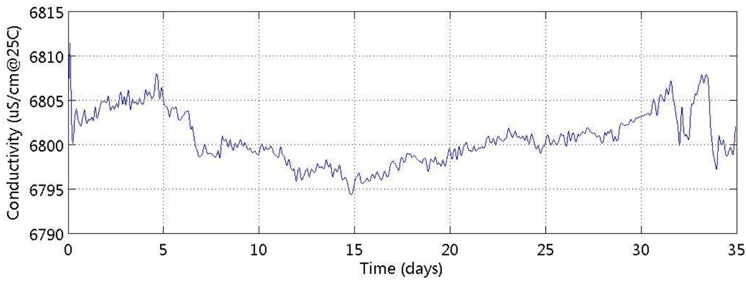

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Figure 10: Frequency analysis of electrical conductivity measurements every 30 minutes from Reference TUBER "2" (a) original data; and after the removal of the mean and trend; (b) Fast Fourier Transform of conductivity measurements after mean and trend is removed; (c) resulting data after the removal of the trend and noise from the signal.

Table 7: Sampling frequency analysis results for Reference TUBER "1", sampling interval = 20 minutes.

Variable	Cut-off Frequency (Hz)	PSD of the Original Signal	PSD of the Filtered Signal	$PSD_{filtered}$ / $PSD_{original}$ (%)	Optimum Sampling Interval (hr)
Temperature	3.60E-04	10.1462	9.2348	91.02	0.1929
Conductivity	5.00E-06	7.93E+07	7.67E+07	96.71	13.889
pH	1.00E-05	55.4257	52.4295	94.59	6.9444
Redox	1.00E-05	9.50E+05	8.700E+05	91.62	6.9444
Dissolved O_2	1.10E-05	2.48E+06	2.41E+06	97.03	6.3131

Table 8: Sampling frequency analysis results for Reference TUBER "1", sampling interval = 40 minutes.

Variable	Cut-off Frequency (Hz)	PSD of the Original Signal	PSD of the Filtered Signal	$PSD_{filtered}$ / $PSD_{original}$ (%)	Optimum Sampling Interval (hr)
Temperature	3.50E-05	1.0196	0.9251	90.73	1.9841
Conductivity	4.00E-06	7.00E+07	6.48E+07	92.60	17.362
pH	4.00E-05	43.7730	39.5330	90.03	1.7361
Dissolved O_2	1.90E-04	9.40E+03	8.55E+03	91.02	0.3655

Table 9: Sampling frequency analysis results for Reference TUBER "2", sampling interval = 30 minutes.

Variable	Cut-off Frequency (Hz)	PSD of the Original Signal	PSD of the Filtered Signal	$PSD_{filtered}$ / $PSD_{original}$ (%)	Optimum Sampling Interval (hr)
Temperature	2.42E-04	0.0326	0.0295	90.29	0.2870
Conductivity	6.00E-05	1.59E+04	1.44E+04	90.67	1.1574
Chloride	3.00E-05	3.55E+07	3.22E+07	90.79	2.3148
NH4	1.70E-04	1.96E+04	1.77E+04	90.33	0.4085
Dissolved O_2	1.75E-04	27.2879	24.6642	90.39	0.3968

The above results of some groundwater quality parameters around the landfill site reveal that the provided data for the temperature variable is noisy data. However, the results of the other variables are acceptable.

4. CONCLUSIONS

A methodology to determine the optimum sampling frequency for the different water quality parameters that being measured for continuous monitoring was developed. The main procedure was first established over a quite good data that provided from a real data of temperature measurements from a river. Then a two case study from the tested mine site and the landfill site were presented to validate the methodology. The obtained results showed that groundwater quality parameters around the mine site could be monitored with sampling interval of 13.899 hrs for temperature, electrical conductivity, pH variables, 1.7 hrs for Redox, and 0.313 hrs for dissolved oxygen instead of the initial 15 minutes intervals without loosing any significant data. The variation in the optimum sampling frequency for each variable depends upon the nature of the provided data, the instrument used, and the initial sampling interval. But in all cases, the results indicated the importance of defining the intervals during the monitoring programme which could lead to a better save in time and costs capacity.

5. ACKNOLEDGEMENTS

The authors acknowledge G. Larry for his efforts to conduct the field measurements at Tara area and also grateful thanks to O'Neill and Ismes S.p.A Company for helping in collecting the data from north Italy.

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طريقة لتحديد الزمن الأمثل لأخذ عينات لتحديد عناصر جودة المياه

في هذا البحث استخدمت بيانات حقلية تم تجميعها من قياسات تمت لرصد عناصر جودة المياه بطريقة مستمرة وعلى فترات زمنية قصيرة تصل إلى 10−40 دقيقة. وقد استخدمت هذه البيانات في تحديد الزمن الأمثل لكل عنصر من عناصر جودة المياه وذلك باعتبار أن البيانات المسجلة بهذه الطريقة يمكن أن تمثل موجة مستمرة مقاسة من كل جهاز رصد حساس (sensor) مع افتراض أن كمية الأخطاء المحتمل حدوثها لا تتعدى 3 % في حالة عمل الجهاز الحساس بصورة جيدة.

في البداية استخدمت بيانات لقياس درجة حرارة المياه تم تسجيلها لفترة زمنية طويلة تصل إلى 6 شهور كل 15 دقيقة من مياه سطحية تم تسجيلها بطريقة دقيقة.

استخدم محول فوريير السريع (Fast Fourier Transformer) لدراسة هذه البيانات وقياس قوة الموجة (Power spectral density) ومن ثم تقديم اقتراح بالطريقة والذي يمكن تعميمه على بقية العناصر والقياسات المتشابهة. ثم تم اختبار الطريقة على مجوعتين مختلفتين من البيانات توفرت من شركتين مختلفتين بهدف تحديد الزمن الأمثل لعدد سبعة عناصر من عناصر جودة المياه الهامة وهي (temperature, pH, electrical conductivity, dissolved oxygen, redox, nitrate, and chloride) والتي يعتاد قياسها لمعرفة درجة جودة المياه خاصة حول مناطق التعدين ومناطق التخلص من النفايات.

وقد أظهرت نتائج تطبيق الطريقة المقترحة إمكان رصد بعض عناصر جودة المياه بزمن يصل إلى أربعة أضعاف الزمن التي يتم استخدامه حاليا لبعض العناصر دون حدوث تغير في المعلومات الرئيسية التي تسجل باستخدام زمن أقل لأخذ العينات مما يوفر في التكلفة والوقت.