Pak. J. Engg. & Appl. Sci. Vol. 10, Jan., 2012 (*p.* 6-20)

Diurnal Variations in Wastewater Characteristics at Main Outfall in Lahore

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Abstract

Variations in the flow and pollutants concentrations during the day were monitored at the Main Outfall disposal station of the city of Lahore. The laboratory analysis of the wastewater samples collected at 2 hour interval on 5th and 6th May, 2009 for pH, temperature, alkalinity, hardness, Biochemical Oxygen Demand (BOD5), $BOD5_{Filtered}$, Total Kjeldahl Nitrogen (TKN), Ammonia Nitrogen (NH_3-N), chlorides, solids, turbidity, sulphates and nitrates were carried out. Average values and standard deviations were determined to assess the type of wastewater treatment. Correlation between BOD5 and $BOD5_{Filtered}$ was developed through regression analysis. Diurnal variations in the Ultimate Biochemical Oxygen Demand (BODU) at the Main Outfall based on Carbonaceous Biochemical Oxygen Demand (CBODU) and Nitrogenous Biochemical Oxygen Demand (NBODU) are also estimated. The ratio between CBODU/NBODU ranges between 0.86 to 1.8 during a day at Main Outfall. This variation is primarily due to the large diurnal variation in CBODU values as a result of industrial activities in the study area. The BOD5/ TKN ratio varies between 3.3 and 6.9 and the calculated BODU (i.e., CBODU + NBODU) was found to be almost double of BOD5 during most part of the day primarily due to inclusion of NBOD. The study results reveal the importance of NBOD while designing the wastewater treatment facilities and implementing a water quality control strategy for the River Ravi.

Key Words: Wastewater Characteristics, Wastewater Flow Variations, Water Quality Monitoring, Ultimate Biochemical Oxygen Demand, Nitrogenous Biochemical Oxygen Demand

1. Introduction

Ravi River located between 846750N & 3355300E and 788350N & 3300500E is one of the five largest rivers and has a number of beneficial water uses including irrigation, domestic water supply, recreational and fisheries in the past (Fig 1). Presently, most of its uses are being seriously affected due to the discharge of untreated domestic and industrial wastewaters from the city of Lahore through a number of wastewater pumping stations and surface drains. These large quantities of wastewater have turned the river almost into a wastewater drain and most of the river reach from North-East (NE) District outfall to Qadirabad Balloki (QB) Link Canal is devoid of oxygen during most of the periods during a year (Fig 1). This condition of the river requires an urgent need of wastewater control actions to improve the river water quality particularly Dissolved Oxygen (DO) concentrations. For this purpose, characterization of wastewater considering diurnal variation is indispensable.

Different water quality parameters are important with respect to wastewater treatment. In this study, wastewater flow, pH, temperature, settleable solids, Suspended Solids (SS), Volatile Suspended Solids (VSS), Total Dissolved Solids (TDS), turbidity, alkalinity, hardness, chlorides, sulphates, nitrates, BOD5, BOD5 (Filtered), TKN and NH_3-N are determined through field and laboratory studies to assess the type of biological wastewater treatment including nitrification. Conventionally, 5-days Biochemical Oxygen Demand (BOD) is determined to assess the wastewater strength which is essentially the Carbonaceous Biochemical Oxygen Demand (CBOD) due to the presence of insufficient nitrifiers during first 5 days of incubation. To estimate the impact of wastewater on ultimate oxygen demand in the river ultimate nitrogenous BOD (NBODU) should also be estimated. Haider & Ali (2010) studied the effect of NBOD as a sink of DO and found it an important process to be considered in water quality management of the River Ravi. Therefore Ultimate BOD (BODU) including Nitrogenous BOD (NBOD) is also determined in this study.

2. Study Area and Methodology

Main outfall discharging about 518,400 m^3/day of wastewater in Ravi River at 34.1Km is one of the largest disposal stations in Lahore (Fig 1). Its catchment is densely populated old residential city alongwith some industrial establishments. However, specific surveys for the type, nature and location of the industry are not available. The sewerage system in the drainage area shown in Fig 1 is partially combined type that receives both domestic and industrial wastewaters with some allowance of storm water as well. Therefore, its wastewater characteristics are analyzed for the purpose of assessing the diurnal variations both in wastewater concentrations and flows to compare the parameters for biological treatment.

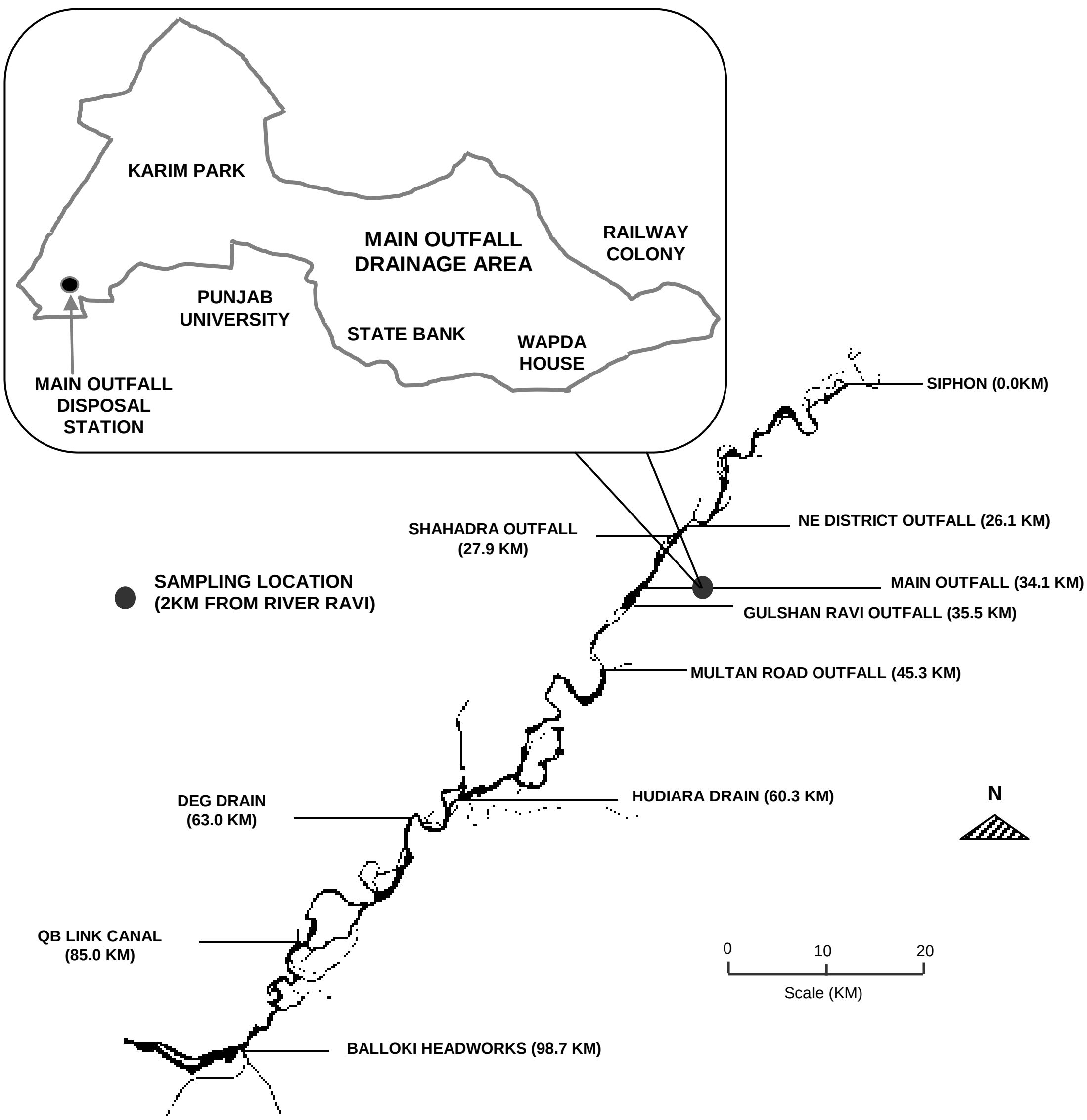
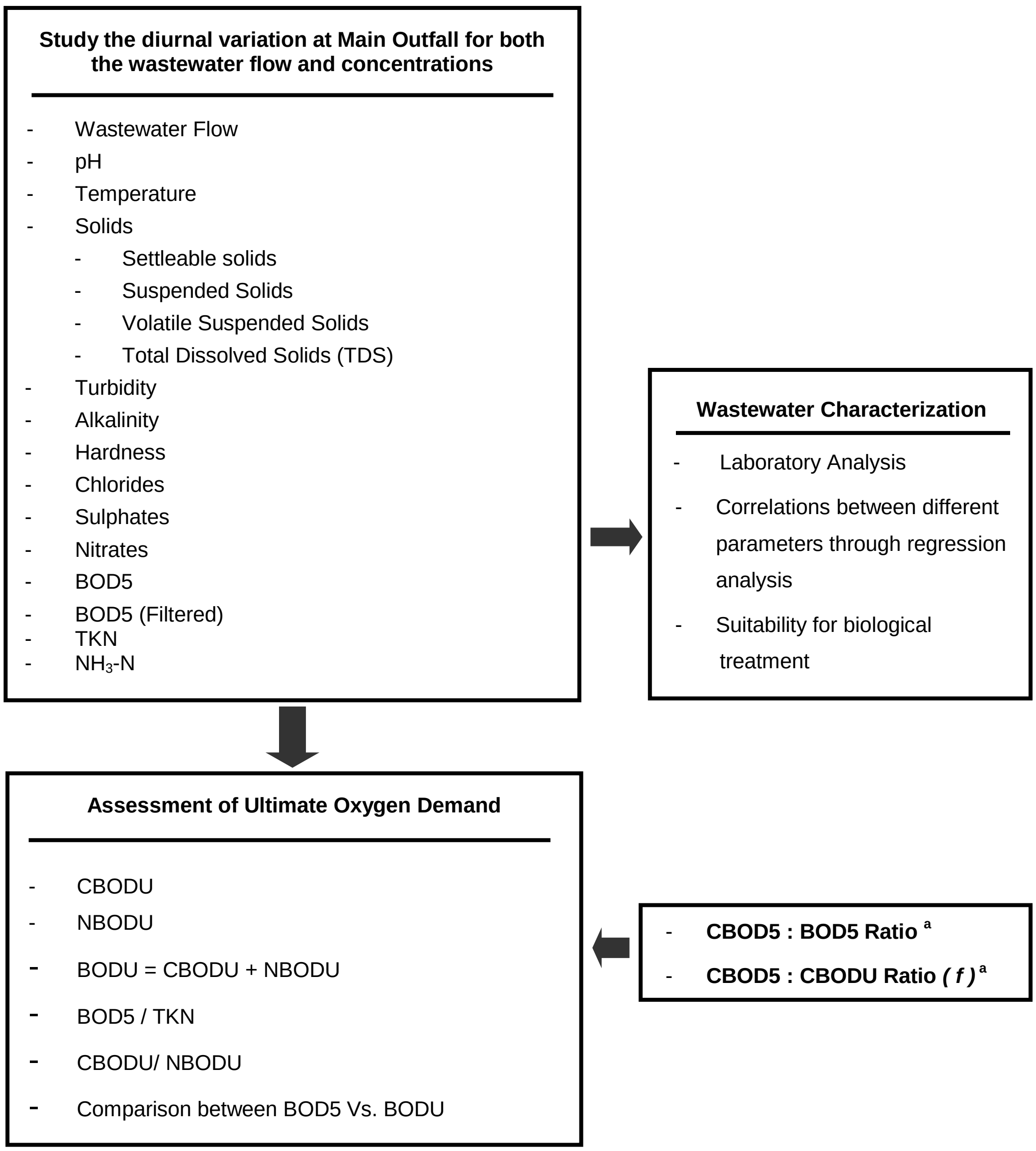


Fig 1: Main Outfall study area showing sampling location along with locations of other wastewater outfalls and surface drains along the Ravi River.

The flows in the River Ravi are highly variable during the year ranging from $10m^3/s$ to as high as $10,000m^3/s$ in dry and wet periods respectively. Water quality problems are primarily associated with low flow conditions. Therefore, dry weather conditions were selected for wastewater sampling and analysis and as such the results of these samples are not representative of the diurnal variations during the wet weather flow.

Wastewater analysis of various water quality parameters are carried out (Fig 2). The BOD5 / CBOD5 and CBODU / CBOD5 have already been established by Haider (2010). These ratios are used to determine CBODU concentration. NBODU is calculated from Total Kjeldahl Nitrogen (TKN) measurements. Total BODU demand is then calculated by adding both the CBODU and NBODU demands. Comparison has been made between the BOD5 and BODU values. Ratio between BOD5/TKN and CBODU/NBODU are also established (Fig 2).



[a] ratios established by Haider (2010) through long-term BOD analysis

Fig 2 Framework of assessment of diurnal variations in wastewater characteristics at Main Outfall

3. Material and Method

A field survey at Main Outfall disposal station was conducted on 5th and 6th May, 2009. The details are given by Haider (2010). Average ambient temperature was about 40^oC and no event of rainfall occurred during the whole sampling period. Twelve wastewater samples were collected at an interval of 2-hour during the whole survey period of 24 hours and tested for different physical and chemical parameters. All the samples were collected from the start of outfall drain (near the disposal station). The length of the drain is 2Km from the sampling point to the point where it joins the River Ravi.

The collection and preservation of the samples was done according to Standard Method No. 1060 (APHA 1998). A single well mixed grab sample was collected from the Main Outfall (Fig 1) at each time interval with the help of an open bucket connected with a rope. The diurnal variation of different wastewater quality parameters was assessed by collecting wastewater samples through the above mentioned arrangement and stored in 5 liter containers after every two hours. The collected samples were transported form main outfall to the Institute of Environmental Engineering & Research (IEER) laboratory within 2 hours and stored at 4^oC for analysis (APHA 1998).

Temperature, pH and Total Dissolved Solids (TDS) were measured in the field with the help of Sension 156 HACH, portable multi-parameter meter for wastewater characterization. Turbidity of the wastewater samples was measured by the Nephelometric Method with Hach 2100AN Turbidimeter (APHA 1998).

Total Suspended Solids (TSS), Volatile Suspended Solids (VSS) and Settleable Solids (SS) were measured according to Standard Method No. 2540 (APHA 1998). Settleable solids were determined in “mg/L” by siphoning 250 mL of the settled samples from a 2 liter beaker for 1 hour as prescribed in the Standard Methods. Suspended solids were determined for these siphoned samples to determine non-settleable solids and the difference from the total suspended solids gave settleable solids in mg/L (APHA 1998).

Alkalinity and hardness of the wastewater samples collected from the Main Outfall were measured according to the Standard Methods No. 2320 and 2340 respectively (APHA 1998). Sulfates in the wastewater samples were measured according to the Standard Method No. 4500-$SO_4^{\ 2-}$, whereas, nitrates and chlorides were measured according to the Standard Method No. 4500-$NO_3^{\ -}$ and 4500-Cl^- respectively (APHA 1998) at IEER laboratories.

BOD tests were conducted according to Standard Method No. 5210 B. With each sample a set of blank and a set of GGA (glucose – glutamic acid) check were also carried out for Quality Control (QC) and Quality Assurance (QA). BOD5 test for filtered and unfiltered samples were also performed as per APHA 1998 standard procedures. Dissolved Oxygen (DO) was fixed at the site by adding 1mL Manganese Sulfate ($MnSO_4$), 1mL alkali-azide reagent and 1mL concentrated H_2SO_4 (APHA 1998). Dissolved oxygen was analysed according to Standard Method No. 4500-O B (i.e., Standard Winkler method) (APHA 1998).

Total Kjeldahl Nitrogen (TKN) was measured according to Standard Method No. 216 (APHA 1971). Ammonia Nitrogen (NH_3 – N) was measured according to Standard Method No. 4500-NH_3-N (APHA 1998).

4. Results and Discussion

4.1 Diurnal Variation in Wastewater Characteristics

The results of the twelve wastewater samples collected at the Main Outfall are presented in Table 1. Diurnal variations for pH, temperature and TDS in the wastewater samples are shown in Fig 3. The pH varied between 6.4 to 7.1 with an average of 6.7 and a small Standard Deviation (SD) of 0.22 during a day. Maximum values slightly greater than 7.0 observed at 4:00AM and 12:00 in the afternoon. However, overall pH variations in the wastewater is almost constant and lies within the required rage of 6.5 – 7.5 to support the growth of micro-organisms in a wastewater treatment plant. These values also qualify for irrigation use (i.e., 6.5 – 8.4) (FAO 1994). Temperature of the wastewater ranged between 26.7 ^oC to 28.5 ^oC (i.e., morning – evening) with an

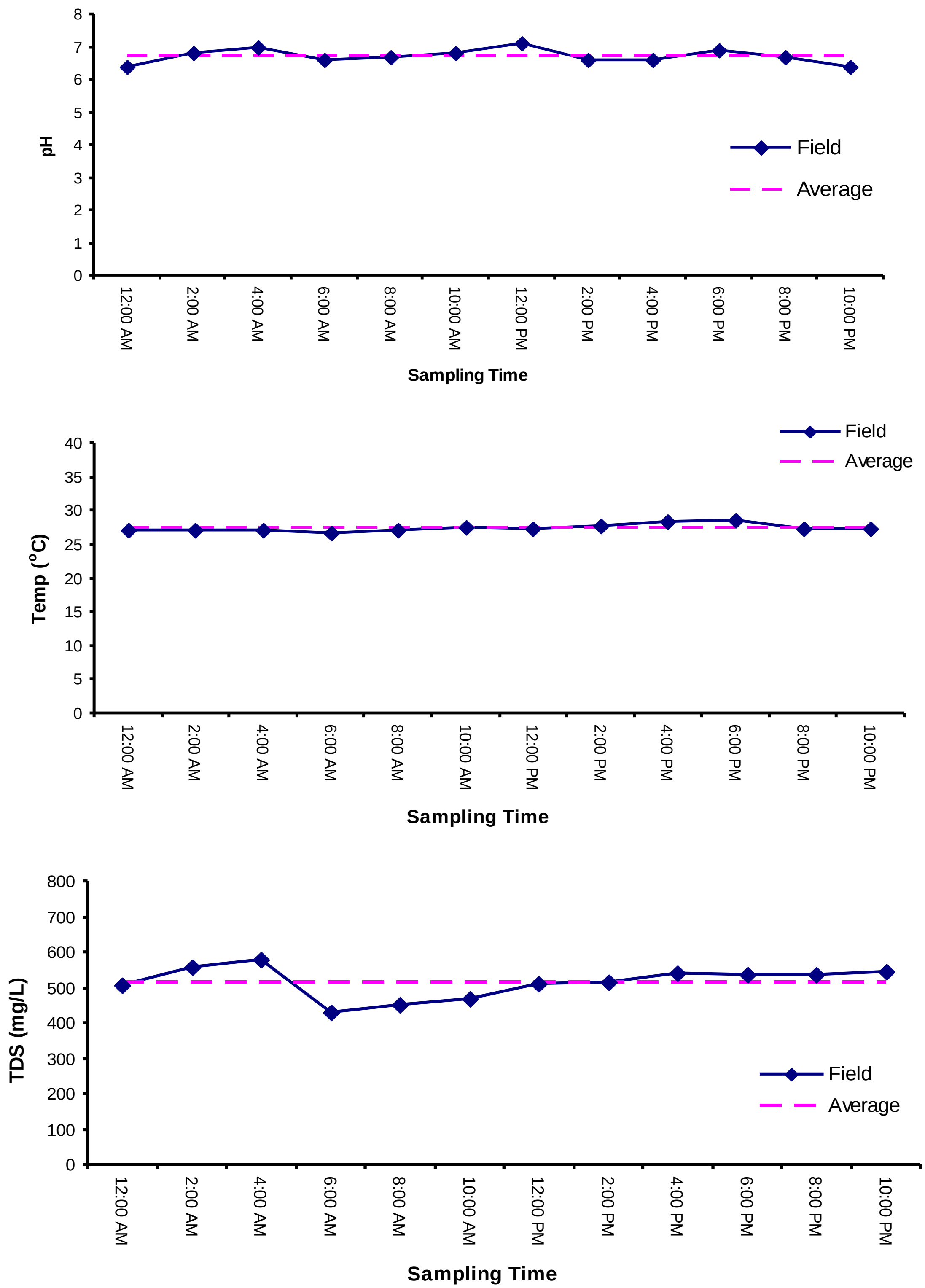


Fig 3: Daily variation of temperature, pH and TDS at Main Outfall

average of 27.4°C with a "SD" of only 0.56°C. The temperature range of 10°C to 40°C is suitable for biological treatment (Sawyer et.al., 2003), which means that the temperature range observed in the wastewater generated from the city of Lahore during the day is suitable for biological treatment during the summer season. No concentration of DO was found in any of the wastewater samples.

The range of TDS in the wastewater samples collected at Main Outfall were observed between 431mg/L to 578mg/L with an average concentration of 514mg/L and "SD" of 45mg/L, which also qualifies for surface irrigation (i.e., 450 – 2000 mg/L) (FAO 1994). Total Suspended Solids (TSS), Volatile Suspended Solids (VSS) and settleable solids were determined as important parameters for design of the primary wastewater facilities (Fig 4a&b). The average values of TSS, VSS and SS were 198, 126mg/L and 106mg/L with the standard deviations of 43mg/L, 27mg/L and 42mg/L respectively. This shows that on average about 65 % of the suspended solids are volatile in nature and about 55% are physically settleable in an Imhoff cone. However, only in two samples collected at 10:00AM and 12:00PM the percentages of the settleable solids are as high as 75% and 65% respectively. In general the values of both the TSS and VSS are higher during the day period than the samples collected during the night time same as other parameters.

A linear regression analysis (R^2 = 0.99) was carried out to establish the relationship between TSS and VSS. The graph is shown in Fig 5 and the mathematical relationship is given as Eq 1.

$$VSS = 0.636\ (TSS) \qquad \textbf{(1)}$$

Turbidity in all of the samples collected during the day was also measured (Fig 5). The turbidity of the samples varied between 110 – 228 NTU with an average and "SD" of 171NTU and 38NTU respectively. The relationship between TSS and turbidity is given as Eq (2) with "R^2" of 0.81 (Fig 7). These results show that by determining the turbidity through a quick test can be used as a rough estimate of TSS and VSS for the Lahore wastewaters.

$$TSS,\ mg/L = 1.16\ (Turbidity,\ NTU) \qquad \textbf{(2)}$$

Alkalinity and Hardness were determined for all of the samples collected from Main Outfall. The laboratory analysis results are shown in Fig 8 a & b respectively. Most of the values were less than 380mg/L with the exception of 2:00AM and 4:00AM values when alkalinity is above 400mg/L. The reason could be some specific night time industrial activities. About 7.07 mg of alkalinity as $CaCO_3$ per mg of NH_3-N is required for growth of the nitrifiers along with an additional amount of residual alkalinity of 70 – 80 mg/L to maintain the pH near 7 to accomplish biological nitrification (Metcalf & Eddy 2003). It means, that for Lahore wastewaters having about 30mg/L of NH_3-N, approximately 300mg of alkalinity as $CaCO_3$ is required. Alkalinity of the Lahore wastewater reflected a small diurnal variation between 330 – 420 mg/L as $CaCO_3$ with an average of 367 mg/L as $CaCO_3$ and standard deviation of 26 mg/L as $CaCO_3$. These results show that sufficient alkalinity is available in the wastewater for biological nitrification.

Hardness varied diurnally from 208 mg/L as $CaCO_3$ in the morning to 368 mg/L as $CaCO_3$ at 6:00PM in the evening (i.e., about 44% higher than the morning value) (Fig 8b). This could be due to the industrial activities in the catchment area. The average hardness of the wastewater was 278 mg/L as $CaCO_3$ with a standard deviation of 46 mg/L as $CaCO_3$ in the samples collected during 24 hours. The waters with hardness concentration of equal to or more than 180 mg/L as $CaCO_3$ are very hard (Droste 2004). Therefore, wastewater generated from the city of Lahore at Main Outfall is very hard.

Sulphates and Chlorides were also determined for all of the samples, the results are shown in Fig 9 a& b. Sulphates ranged between 120 mg/L to 192mg/L with an average value of 151mg/L and standard deviation of 24mg/L. Whereas chlorides were observed to be between 50mg/L to 120mg/L with an average of 96mg/L and standard deviation of 20mg/L. The range of chlorides concentration also qualifies the required chlorides concentration of less than 140mg/L for surface irrigation (FAO 1994). Higher sulphates values were observed between 10:00AM and 6:00PM due to certain industrial activities in the catchment area. Chlorides concentration however remained around average value with the exception of the sample collected at 6:00AM.

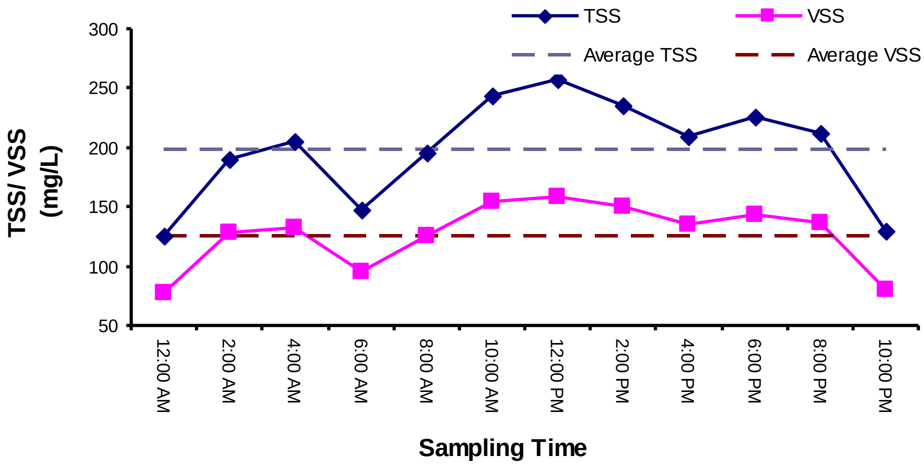


Fig 4a: Diurnal variation of TSS and VSS at Main Outfall

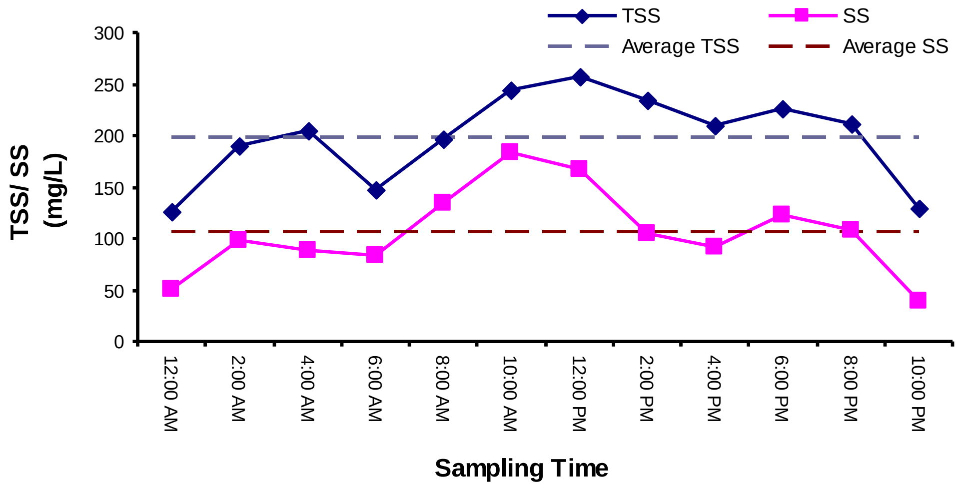


Fig 4b: Diurnal variation of TSS and SS at Main Outfall

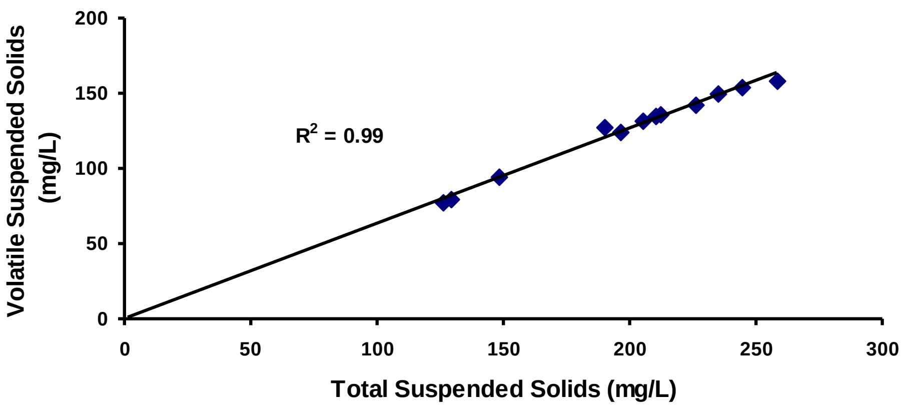


Fig 5: Correlation between TSS and VSS

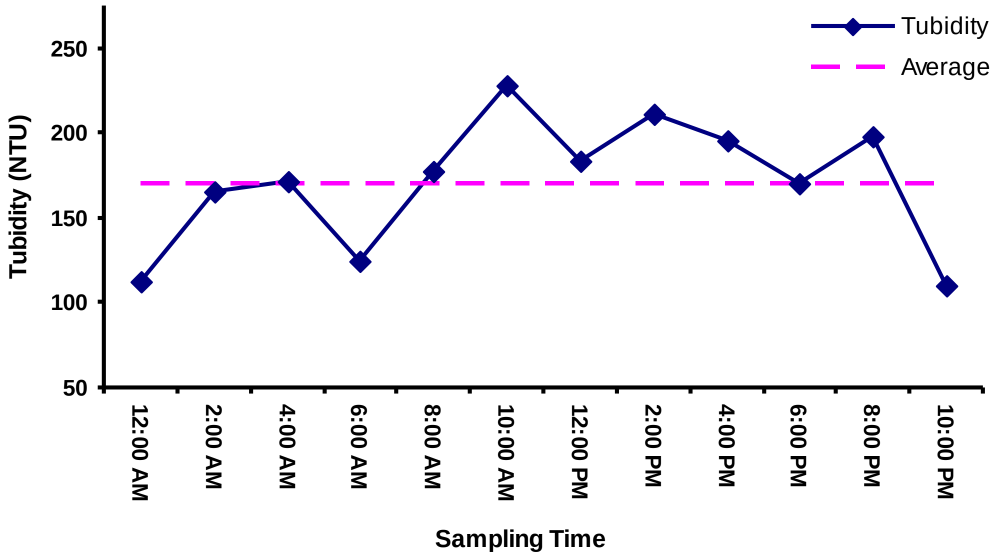


Fig 6: Diurnal variation of Turbidity at Main Outfall

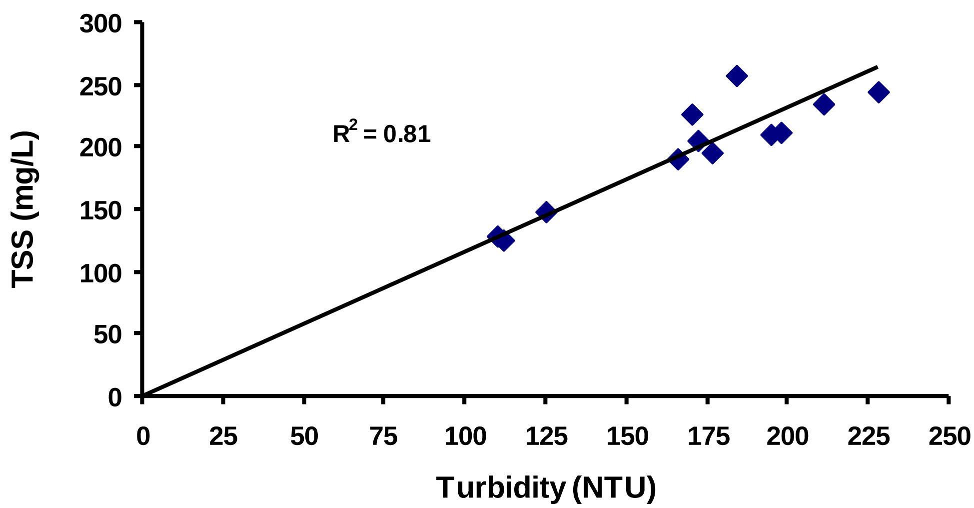


Fig 7: Correlation between Turbidity and TSS

TKN is an important parameter for DO modeling of the rivers, especially when the model used involves Nitrogenous Biochemical Oxygen Demand (NBOD) alongwith Carbonaceous Biochemical Oxygen Demand (CBOD). NDOBU is also significant in domestic as well as some industrial wastewaters and its estimation is very important both for the design of wastewater treatment facilities and also to assess the impact on the receiving water body where the nitrifiers are available in sufficient population to exhibit NBOD. TKN and NH_3-N were measured with average values of 40.9mg/L and 26.4mg/L respectively, the results are shown in Fig 10. Small standard deviations were formed for TKN and NH_3-N as 3.5 and 1.9 respectively. No nitrates were found in any of the samples.

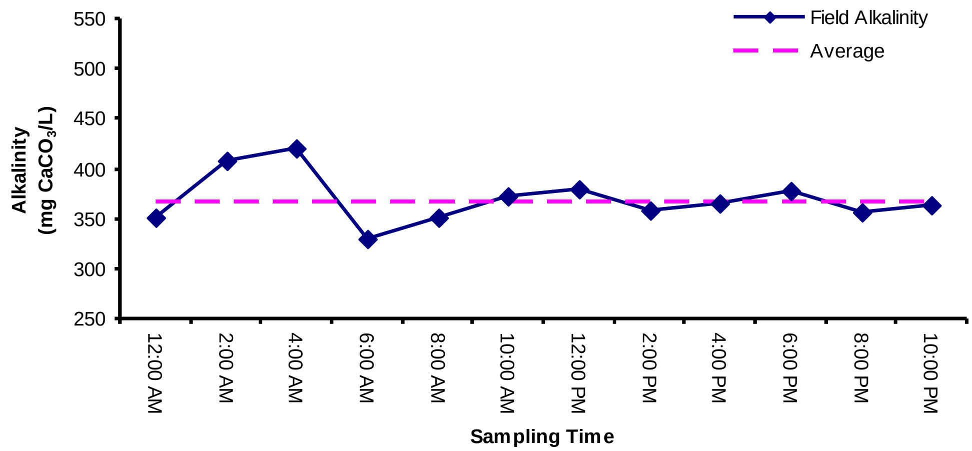


Fig 8a: Diurnal variation of Alkalinity at Main Outfall

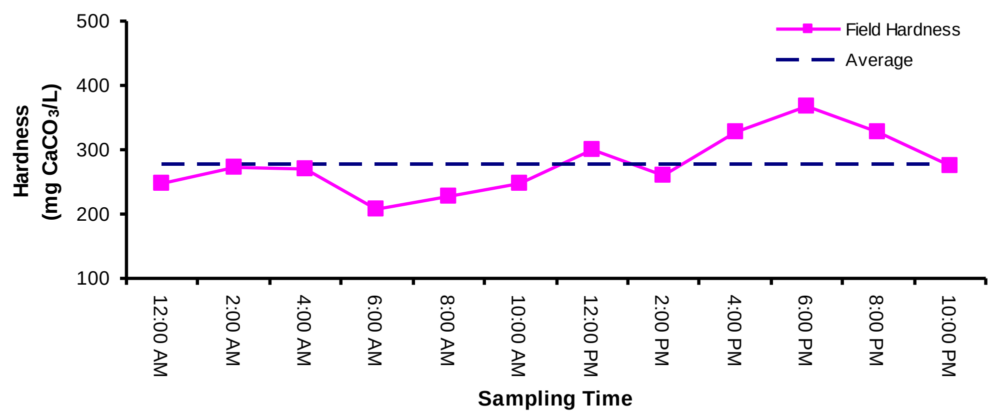


Fig 8 b: Diurnal variation of Hardness at Main Outfall

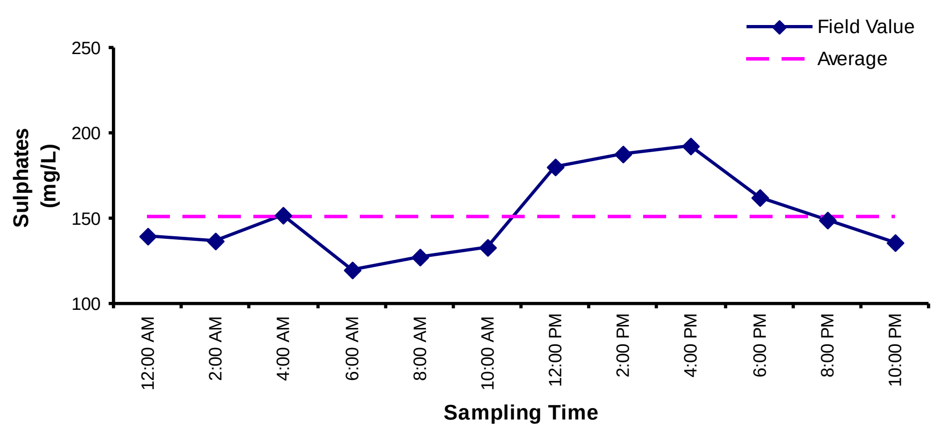


Fig 9 a: Diurnal variation of Sulphates at Main Outfall

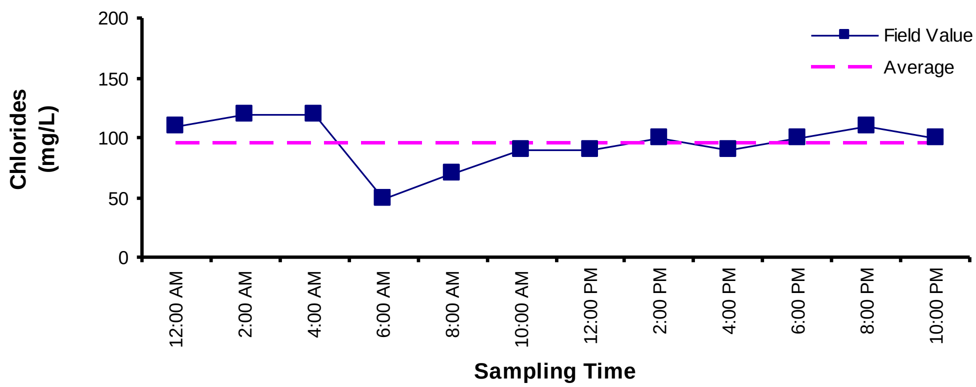


Fig 9 b: Diurnal variation of Chlorides at Main Outfall

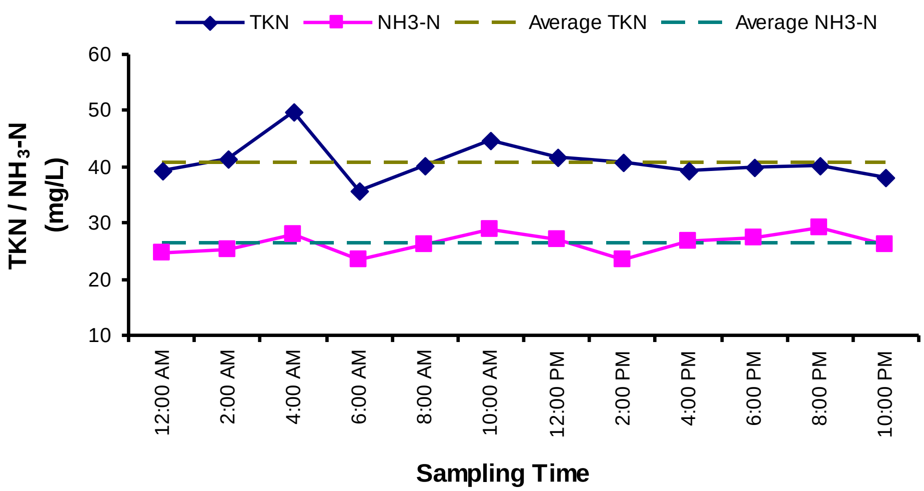


Fig 10: Diurnal variation of TKN and NH_3-N at Main Outfall

Dissolved oxygen is one of the most important parameter to describe ecological health of a river system and BOD is the most important controlling parameter for DO in the rivers. In this study, BOD5 tests were performed for both filtered and unfiltered samples, the results of the tests are shown in Fig 11. The average values of BOD5 and $BOD5_{(Filtered)}$ were 189 mg/L and 87mg/L, whereas, the standard deviations were 53mg/L and 31mg/L respectively. The large variation between 117mg/L in the sample collected at 6:00AM in the morning to 293mg/L in the sample collected just after 4 hours at 10:00AM. The reason for this large variation could be the industrial wastewater from the catchment area of Main Outfall disposal station. Other values lied in between these two extremes. A sudden drop up to 180mg/L was observed in the sample collected at 12:00PM in the after-noon. This could be due to low industrial activity and relatively small contribution from the domestic sources. As the industrial activity normalizes, BOD again increases to 282mg/L at 2:00PM.

No significant variation was observed between 6:00PM to 6:00AM in the BOD5 values. Similar behavior was observed in filtered samples with lower concentrations. A relationship between BOD5 and $BOD5_{(Filtered)}$ is also established through regression analysis. The regression graph is shown in Fig 12 and the relationship is given as Eq (3) with R^2 value of 0.74. These results show that about 54% the total BOD is in particulate form.

$$BOD5_{(FILT)} = 0.46\ (BOD5) \qquad \textbf{(3)}$$

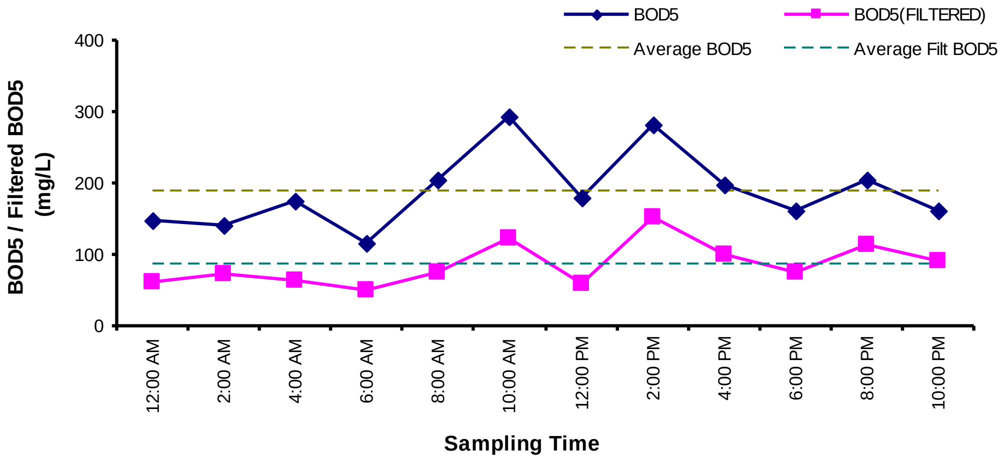


Fig 11: Diurnal variation of BOD5 and BOD5 $_{(FILT)}$ at Main Outfall

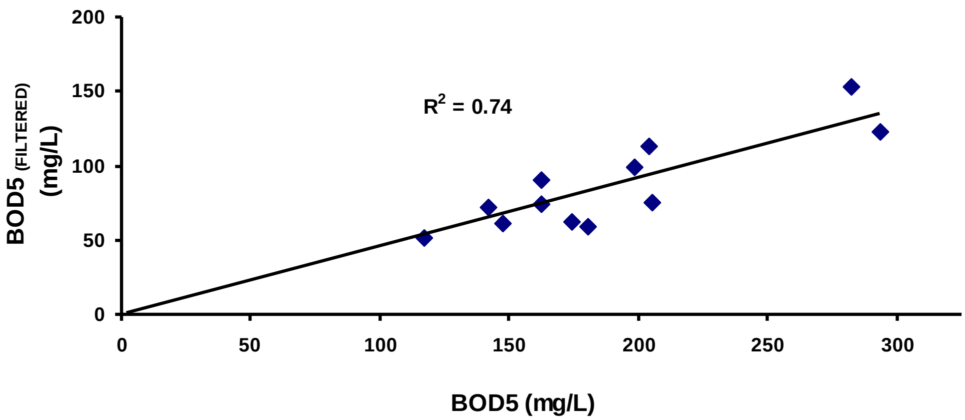


Fig 12: Correlation between BOD5 and BOD5 $_{(FILT)}$

The variations in TKN are less pronounced than the variation in BOD, although the highest value of TKN was noted at 4:00AM when the BOD was not the highest. However, when the BOD was highest at 10:00AM in the morning the TKN values was 44.8mg/L, which was not the highest but was close to the highest value.

Commonly the ratio between carbonaceous and nitrogenous organic matter is expressed as BOD5/ TKN ratio. Karagozoglu and Altin (2003) determined the BOD5/ TKN ratio for the domestic wastewater of a medium size city of Sivas in Turkey. According to their estimates the ratio varied between 3.1 and 9.5. In this study the diurnal variation of BOD5 / TKN ratio varies between 3.3 and 6.9 during a day, which is lower than the above study. These results further support the need of site specific studies rather than relying on literature values for the design of wastewater treatment facilities.

4.2 Wastewater Flow Variations

Wastewater flow data at Main Outfall was collected from Waster and Sanitation Agency – Lahore Development Authority (WASA-LDA) during the whole sampling day to observe the wastewater flow variations as well (i.e., 5th and 6th May 2009). The hourly flow variations along with average values during the day of sampling are shown in Fig 13. The minimum and maximum observed flows were 3.0m^3/s and 6.0m^3/s respectively.

It can be seen in the Fig 13 that flow gradually decreases from 4.2 m^3/s around midnight to 3.0 m^3/s at

6:00AM the morning. There is dramatic increase between 6:00AM to 8:00AM due to early day activities. After that there is a small decrease up till 10:00AM. Flow gradually increases from $3.8m^3/s$ to $4.9\ m^3/s$ from 10:00AM to 4:00 PM respectively. The values then increases to $6.0m^3/s$ (i.e., the maximum observed discharge) at 6:00 PM. This is due to the fact that the wastewater from the entire drainage area of the Main Outfall disposal station has reached to the wet well. The wastewater flow then gradually decreases to a value of around $5m^3/s$ during the night time (8:00 PM– 10:00PM). However, an increasing trend was always observed during the working hours as shown in the Fig 13.

The study results also show that almost all the wastewater parameters including flow were minimum at 6;00 AM in the morning. At this time both the domestic and industrial activities have not been initiated in the city of Lahore.

4.3 Estimation of Ultimate CBOD, NBOD and BOD

As discussed earlier, BODU includes both the CBODU and NBODU for the assessment of the impact of the whole organic matter on the receiving water body. Haider (2010) determined the ratio between BOD5/ CBOD5 for the Main Outfall using the nitrification suppressant and also estimated CBOD bottle rate constants *(K)* and the ratio *" f "* between CBODU / CBOD5 through long-term BOD analysis (Fig 14). For most of the municipal wastewater BOD5 is considered equal to CBOD5. The results of long-term BOD analysis shown in Fig 15 reveal that some nitrification is completed in first 5 days (i.e., BOD5/CBOD5 = 1.16). The ratio *"f"* mathematically can be represented as;

$$f = \frac{CBODU}{CBOD5} = \frac{1}{1 - e^{-5K}} \qquad \textbf{(4)}$$

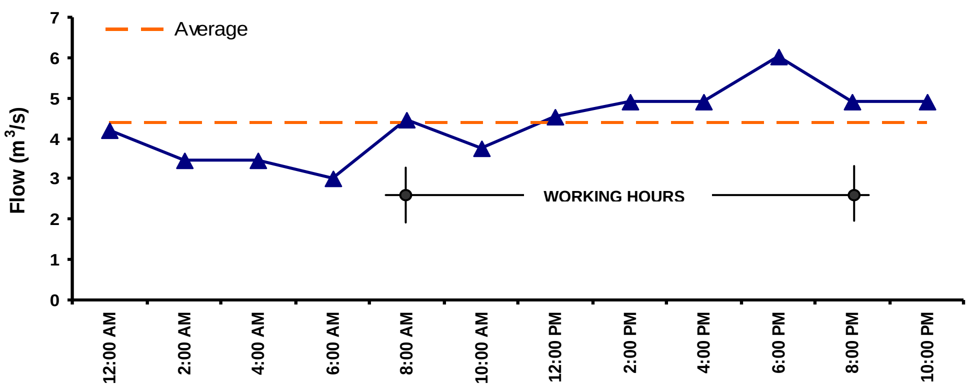


Fig 13: Diurnal wastewater flow variation on 5th and 6th May, 2009 at Main Outfall

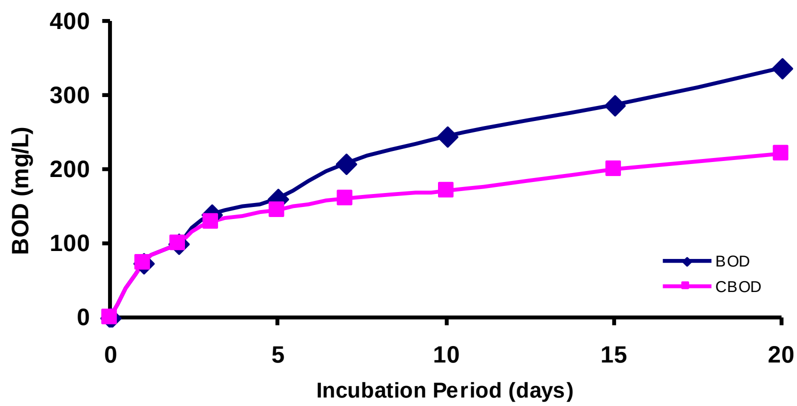


Fig 14: Long-term BOD analysis at Main Outfall (Source: Haider 2010)

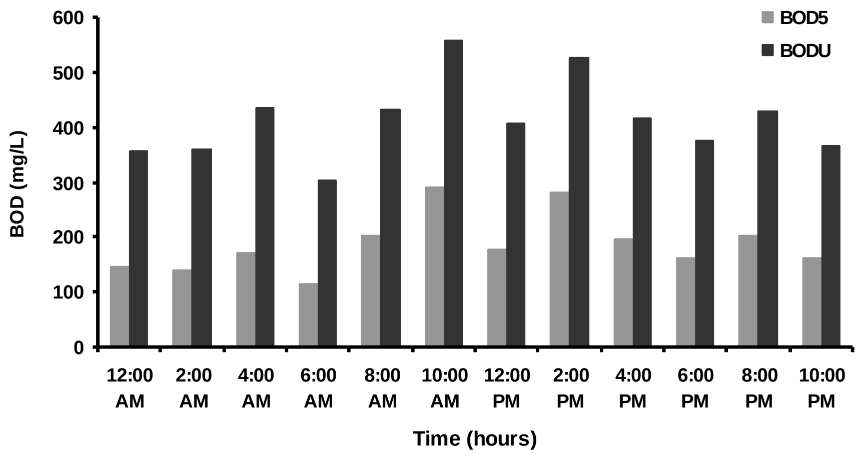


Fig 15: Diurnal variations of BOD5 and BODU at Main Outfall

where K is the CBOD bottle rate constant. In this work, CBODU values are calculated by determining the CBOD5 from BOD5 and then CBODU by multiplying CBOD5 with the factor *"f"* (Table 2). The estimated value of *"f"* by Haider (2010) was 1.4.

The NBOD is the amount of oxygen required to oxidize ammonia to nitrites and then nitrites to nitrates during the process of nitrification. A generalized nitrification process in wastewaters can be expressed with the help of following equations (Thomann & Mueller 1987);

$$NH_4 + 1.5O_2 \xrightarrow{Nitrosomonas} 2H^+ + H_2O + NO_2^- \quad \textbf{(5)}$$

In this first step, about 3.43g of oxygen is utilized for oxidation of 1g of nitrogen to nitrite, whereas, the nitrites are then further oxidized by Nitrobactors as;

$$NO_2^- + 0.5O_2 \xrightarrow{Nitrobactor} NO_3^- \quad \textbf{(6)}$$

In this step about 1.14 g of oxygen is required for 1 g of nitrite-N oxidation to nitrate-N. Therefore, the overall oxygen utilized is 4.57g per gram of ammonia-N oxidized to nitrate-N during the nitrification process. Therefore, the total concentration of nitrogenous organic matter can be estimated by using the following equation;

$$NBODU = 4.57\ TKN \quad \textbf{(7)}$$

BODU concentration can then be calculated as;

$$BODU = CBODU + NBODU \quad \textbf{(8)}$$

Table 2: Estimated CBODU, NBODU and BODU Variations at Main Outfall

Sr #	Time	BOD5 (mg/L)	CBOD5 (mg/L)	CBODU (mg/L)	NBODU (mg/L)	BODU (mg/L)	BODU/ BOD5	CBODU/ NBODU
1	10 AM	293	253	354	205	559	1.9	1.7
2	12 NN	180	155	217	191	408	2.3	1.1
3	2 PM	282	243	340	186	527	1.9	1.8
4	4 PM	198	171	239	180	419	2.1	1.3
5	6 PM	162	140	196	182	377	2.3	1.1
6	8 PM	204	176	246	184	430	2.1	1.3
7	10 PM	162	140	196	174	369	2.3	1.1
8	12 MN	147	127	177	179	357	2.4	1.0
9	2 AM	142	122	171	189	360	2.5	0.9
10	4 AM	174	150	210	228	438	2.5	0.92
11	6 AM	117	101	141	164	305	2.6	0.86
12	8 AM	205	177	248	184	432	2.1	1.3

The estimates of CBODU, NBODU and BODU concentrations are presented in Table 2. The average value of BODU was 415mg/L with a standard deviation of 72mg/L. The average values of CBODU and NBODU were 228mg/L and 187mg/L with standard deviations of 64 and 16 respectively. The minimum BODU value of 305 mg/L was observed at 6:00AM in the morning, whereas maximum BODU of 559 mg/L was found at 10:00AM. A comparison is made between BOD5 and BODU concentrations in Figure 15. It can be seen in Figure 15 that BODU was more than double than the BOD5, primarily due to inclusion of NBOD. Maximum values can be observed between 8:00AM in the morning to 8:00 PM in the evening. The ratio between CBODU/NBODU ranged between 0.9 and 1.8. These results given in Table 2 reveal that NBODU was almost equal to CBODU in domestic wastewater of Lahore between 6:00 PM to 6:00AM. However, during the day time (i.e., 8:00AM – 4:00PM) CBODU is higher than NBODU primarily due to industrial activities in the Main Outfall catchment area. High values of NBODU in the Lahore wastewater suggest that biological treatment facilities should be designed for both the BOD removal and nitrification as well.

5. Conclusions

Temperature, pH and TDS in the Lahore wastewater do not change significantly in a diurnal cycle. pH values in the wastewaters generated from the Main Outfall from Lahore meet the required rage of 6.5 – 7.5 for the growth of micro-organisms in wastewater treatment. The average values of TSS, VSS and SS are 198, 126mg/L and 106mg/L respectively with about 65 % of the suspended solids being volatile in nature and about 55% are physically settleable in an Imhoff cone at Main Outfall. The turbidities of the samples were observed to range between 110 – 228 NTU with an average value of 171NTU.

Sufficient alkalinity is available in the wastewater for biological nitrification with a diurnal variation between 330 – 420 mg/L as $CaCO_3$ with an average of 367 mg/L as $CaCO_3$. Due to industrial activities relatively large variations are observed in hardness from 208 mg/L as $CaCO_3$ in the morning to 368 mg/L as $CaCO_3$ in the evening, which is about 44% higher than the morning value. These results also show that wastewater generated from the city of Lahore at Main Outfall is very hard. The range of chlorides concentration qualifies the required chlorides concentration of less than 140mg/L for surface irrigation (FAO 1994).

TKN and NH_3-N were measured with average values of 41 mg/L and 26 mg/L respectively. Small standard deviations were observed for TKN and NH_3-N as 3.5 and 1.9 respectively. Concentration of nitrates was nil in all of the samples. A large variation between 117mg/L to 293mg/L in the sample collected for BOD5 is observed due to the industrial activities in the catchment area of the Main Outfall disposal station. About 54% of the total BOD is in particulate form. A significant variation between BOD5 / TKN ratio of 3.3 – 6.9 during a day was observed.

CBODU at Main outfall varies between 141mg/L to 354mg/L with an average and standard deviation of 228mg/L and 64mg/L respectively. Based on the nitrogen measurements, NBODU concentration at the Main Outfall varies between 164 and 228 mg/L during a day with an average concentration and standard deviation of 187mg/L and 16mg/L. CBODU/ NBODU ratio varies between 0.86 and 1.8, which is mainly due to large diurnal variation in CBODU concentration due to industrial activities in the study area. Calculated BODU (i.e., CBODU + NBODU) was found to be more than double of BOD5 during most part of the day primarily due to inclusion of NBOD. Therefore, NBOD must be considered while designing the wastewater treatment facilities to implement a water quality control strategy for the River Ravi.

Large quantities of wastewater (i.e., 518,400 m^3/day) are being collected at the Main Outfall, and thus require expansive wastewater treatment facility to conserve water quality of the River Ravi. It is therefore suggested that sustainable wastewater reuse and recycling methods be introduced for both the residential and industrial areas. These technologies will reduce the pollution load to the River Ravi and will also conserve the ground water resources of Lahore. Furthermore, collection and transportation of wastewater from the outfalls located along left side of the river to downstream of Hudiara Drain (Fig 1) for a combined wastewater treatment facility can also be investigated to avoid construction and operational issues associated with number of treatment plants if provided at individual outfall.

6. Acknowledgements

The research work presented in this paper is based on the PhD research work of the first author which was funded by the University of Engineering and Technology, Lahore. The authors acknowledge the support of laboratory staff for sample collection and laboratory analysis.

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