STORM WATER QUALITY AND POLLUTANTS SURFACE-ACCUMULATION RATES IN KHARTOUM

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مُسْتَخْلَص

قدمت نتائج تحليل نوعية الجريان السطحي لمياه الأمطار في سبعة وعشرين موقعاً موزعة مكانياً فوق ولاية الخرطوم خلال أربعة أحداث أمطار مختلفة فى شهرى أغسطس وسبتمبر من عام 2006. استخدمت هذه النتائج في حساب معدلات تراكم الملوثات السطحية ونوقشت العلاقة بين خصائص التلوث فى مياه الجريان السطحي مع ممارسات الادارة البيئية في منطقة الخرطوم. مثلت العينات مواقع مختلفةلاستخدامات الأرض مثل الأراضي السكنية والتجارية والزراعية والصناعية، والمناطق الريفيه حسبت متوسط التراكيز لهذه الملوثات لموسم الامطار اغسطس - اكتوبر 2006. وجد متوسط التراكيز لكل من $BOD, COD, NO_3^-, TP, NH_3$ كالاتى mg/l $45.8, 854.3, 33.5, 2.9, 14.1$ على التوالى.وكان المتوسط الوزني لتراكيز كل من BOD وCOD فى كل من الأراضى السكنية والتجارية mg/l $46.8,\ 511.9$ *and* $58.8,\ 1368.8$ والتى تعتبر كبيرة إذا ما قورنت بنتائج البرنامج القومي للجريان السطحي فى المدن الامريكية US National Urban Runoff Program 10.0, 73.0 *and* 9.3, 57.0 mg/l على التوالى الأمر الذى يؤكد على ضرورة تفعيل الإدارة البيئية وضبط الجودة لنوعية مياه الجريان السطحى لولاية الخرطوم. وجد أن متوسط تراكيز الملوثات يتناقص مع زيادة عدد الأمطار الحادثة وكمية مياه الأمطار. كما أن هذه التراكيزتزيد بزيادة الفترة الزمنية بين الأمطار. لوحظ ان أكبر إزالة للملوثات 90% تمت فى الأمطار الحادثة فى شهر سبتمبر، عليه يمكن التركيز على ضبط الجودة والإدارة البيئية هذا الشهر. طبق نموذج حسابي لحساب كمية ومعدل تراكم الملوثات لكل وحدة مساحة من ولاية الخرطوم. وجد ان كمية الملوثات $BOD, COD, NO_3^-, TP, NH_3$ لوحدة المساحة 110.7, 4400.5, 23.8, 0.7, 13.4 g/km^2 ومعدل تراكم هذه الملوثات 5.4, 161.9, 1.6, 0.06, 0.8 g/km^{2}d . حيث يلاحظ زيادة كمية COD ومعدل تراكمها، مما يدل على كثرة الاستعمالات للمنتجات الصناعية.

ABSTRACT

The results of monitoring storm water quality at twenty seven locations distributed spatially over the Khartoum state during four rainfall events in August and September of 2006 are presented. The storm water quality data were used to calculate pollutants surface accumulation rates and a correlation of storm water runoff pollution characteristics with the environmental management practices in the Khartoum area is discussed. The sampling locations represented various land uses such as residential, commercial, agricultural, industrial, and open rural areas and mean concentrations were calculated for the rainy season Aug-Oct 2006. Weighted mean concentrations of $BOD, COD, NO_3^-, TP, NH_3$ for the state were found to be in the order of $45.8, 854.3, 33.5, 2.9, 14.1$ mg/l respectively. The BOD and COD weighted mean concentrations for residential and commercial land uses in Khartoum $46.8,\ 511.9$ *and* $58.8,\ 1368.8$ mg/l far exceeded the U.S. National Urban Runoff Program (NURP) mean EMC values of $10.0,\ 73.0$ *and* $9.3,\ 57.0$ mg/l respectively indicating requirement for environmental management and quality control of the urban runoff from Khartoum state. The average pollutants concentrations were found to decrease with the order of rainfall event during the year, decrease with increased rainfall amount, and increase with increased duration between events. The first flush effect was observed, however, over 90% of pollutants are washed by September rain and good environmental management and control practices should focus on this month. A model was developed to estimate equilibrium pollutant surface coverage and pollutants accumulation rates in Khartoum state. Equilibrium pollutant surface coverage were found to be $110.7,\ 4400.5,\ 23.8,\ 0.7,\ 13.4$ g/km^2 and the pollutants accumulation rates were found to be $5.4,\ 161.9,\ 1.6,\ 0.06,\ 0.8$ g/km^{2}d for $BOD, COD, NO_3^-, TP, NH_3$ respectively. The high COD mean weighted concentrations, equilibrium surface coverage, and accumulation rate indicate the high amount of pollution encountered from the use of industrial products and other refractory organics from all sources.

Keywords: Urban runoff pollution, Environmental planning, land use planning,l Watershed management.

1. INTRODUCTION

Khartoum state which is currently undergoing a 25-year planning process lies entirely within the Nile system catchment area and contribute directly to the Nile system flow and water quality. Other seasonal streams coming from outside the Nile system catchment area penetrate the state and deliver considerable quantities of water to the White Nile, the Blue Nile and the main Nile.

A huge urban growth occurred in Khartoum state during the last 10 years and this urbanization has a significant impact in storm water quality. The current population of Khartoum is estimated to be eight millions currently compared to three and half millions back in 1993 composing more than 45% of the urban population in the Sudan [1]. The total Khartoum area has increased 10 folds during the previous twenty years.

Upon development of an urban area the artificial surfaces increase the amount of surface runoff in relation to infiltration, and therefore increasing the total volume of runoff and decrease runoff period [2]. These effects, obviously has strong implications on water quality.

Urban runoff quality, in general, is greatly influenced by rainfall and catchment characteristics including environmental management. The catchment characteristics include

1. Geographical location
2. Road and traffic characteristics
3. Buildings and roofing types
4. Weather, particularly rainfall
5. Land use distribution
6. Environmental management practices

The purpose of this paper is to study the runoff water quality from and to estimate the pollutants accumulation rates on the surfaces of Khartoum state. Also, a correlation between the environmental management practices and the degree of pollution encountered in storm water is established.

This work is critical since all urbanized communities within the ten Nile basin countries and within the Nile catchment area is built on the Nile system banks, and controlling their pollution load is extremely important in managing the Nile system water quality and environment. In addition, storm water quality is an important indicator of sound environmental management and it can be used effectively to mitigate environmental degradation and designate land uses for better planning of urban areas.

2. Study Area

The Khartoum state, with an area of 22,000 km2 approximately, has a short cool winter and a long hot dry season, which is intercepted by a hot humid season (July- September), during which most of the annual rainfall (167 mm) occurs.

Khartoum state is divided into residential, commercial, industrial (almost 70% of the countries' industrial production is manufactured in the Khartoum state [3], agricultural and open rural areas where nomadic pastoralism life patterns are dominant. The expansion and allocation of areas among these various types of uses is unplanned and is taking place, sometimes, due to other factors such as displacements due to war and other crisis which is bringing Internally Displaced Persons (IDPs) in fat numbers to reside in camps around and inside the urban Khartoum area. The current division the total state area among various land uses is shown in Figure 1.

The state capital, Khartoum is generating about 7 000 tons of waste per day (0.8 kg/d/capita) in households, of which 51% soil, 35% food, 9% paper and cardboards, 2% plastic, and 2% wood and 2.2 % metals [4]. Poor collection services and improper disposal at open dump sites characterize solid waste management practices. All types of waste hospital, industrial, hazardous and household are collected together and disposed off similarly. Commercial areas are crowded with street sellers and sometimes storm water drains are used to display their merchandise leading to accumulation of dirt in these drains and eventually storm water contamination. Agricultural activity uses many chemicals unavoidably and it drains directly into the Nile system and industrial areas are sumps of smelly liquid waste in many cases since no proper drainage/treatment is provided for industrial wastewater. The number of automobiles has risen dramatically over few years, from few thousands to 66,000 currently and are mostly hand cleaned all over the state and without appropriate drainage for their waste and lubricants. All of these practices affect the quality of storm water significantly.

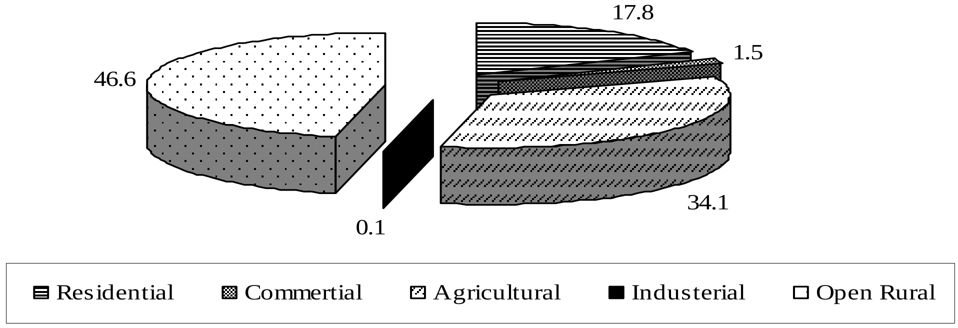


Figure 1: Land Use in Khartoum State (2006)

Important trend in the environmental management in Khartoum state can be summarized as follows:

1. There has been a decline in the quality of the built environment in many inner cities, towns and suburbs due to concentration of internally displaced people camps (IDPs). The green areas have been replaced by housing, factories, and office parks.
2. Sprawling suburbs are converting open rural farmlands, forests, and natural areas to housing subdivisions etc…
3. The sprawling land use patterns are fueled by heavy energy consumption in cars and trucks
4. Development has proceeded faster than new infrastructure (sewer and water facilities, roads, and schools) can keep pace or old infrastructure can be maintained.
5. Urban sprawl has led to serious environmental degradation, urban runoff, cars and trucks air pollution etc.
6. The state has not yet taken full advantage of opportunities for energy conservation and alternative energy sources.
7. The state has not found satisfactory ways to recycle, reuse, or dispose of solid and hazardous waste.
8. Adequate supplies of clean water are becoming increasingly important as the population continues to grow.

3. Experimental Plan and Approach

Random water samples were collected from at 27 sampling locations representing different land uses; residential, commercial, agricultural, industrial and open rural area, upon four rainfall events during the rainy season from August to October of 2006. The samples were analyzed for BOD using standard 5-days BOD test, COD using the open reflux apparatus, nitrate using Hanna nitrate test kit, total phosphorus (TP) and ammonia using Hanna multi-parameter meter C200.

Khartoum state main seasonal streams are ungauged and only estimates of their runoff can be made based on meteorological data. In this paper the Soil Conservation Services (SCS) method [5,6] was used to predict the total amount of flow contributed by the Khartoum state to the Nile flow. The calculated total flow contribution is compared to estimates made by others.

4. Results and Discussion

4.1 Event Mean Concentrations (EMC)

Since the data records consist of only few events; weighting the individual storm concentration by the runoff volume for the storm event can achieve greater accuracy. The mean weighted concentration for each event for certain land use can be determined using the following formula [7]:

$$C_e = \sum_{i=1}^{n} \frac{C_i \times C_i}{C_T} \qquad (1)$$

Where:

$C_e =$ Mean weighted concentration in a storm event for certain land use

$C_i =$ Concentration of the sample (i) in the storm event.

$C_T =$ Total concentration of the samples for the land use in the storm event.

$n =$ The total number of the samples took from the same land use.

The mean concentration for the whole season for the same land use is then can be calculated using the following formula:

$$C_a = \sum_{i=1}^{m} \frac{C_e \times V_i}{V_T} \quad (2)$$

Where:

$C_a =$ The mean concentration for certain land use

$V_i =$ Runoff of the storm (i) in the rainy season.

$V_T =$ The total Runoff in the rainy season.

$m =$ Number of significant storm events in the rainy season

The weighted mean concentrations from different land uses and for different pollutants calculated using Equation (1) are shown in Figure 2. The variation of mean weighted COD concentrations with total rainfall depth and duration between events is shown in Figure 3.

Figure 2 indicates that the most polluting land uses are the commercial and industrial where they contribute much more than the other land uses in terms of concentration. The least polluting land uses are the open rural and agricultural land uses with the residential land use contributing high BOD concentrations almost as much as the industrial land use. Nitrate and phosphorous are found primarily in agricultural lands, but it is also important to know that main contribution of nitrate is coming from industrial and residential areas indicating poor wastewater drainage and management. Overall the BOD and COD weighted mean concentrations for residential and commercial land uses in Khartoum $46.8,\ 511.9\ and\ 58.8,\ 1368.8\ {}^{mg}\!/_{l}$ far exceeded the U.S. National Urban Runoff Program (NURP) mean EMC values of $10.0,\ 73.0\ and\ 9.3,\ 57.0\ {}^{mg}\!/_{l}$ respectively [7] indicating poor environmental management of the urban Khartoum area.

The COD mean weighted concentrations for the whole state were calculated and correlated with the order of storm in the season and it was found out that earlier storms contain the highest COD as will be discussed later. In addition Figure 3 clearly indicates the exponential decrease of COD with amount of rainfall where the wash volume decrease the concentration and the exponential increase of COD with duration of events due to increased COD surface accumulation periods.

4.2 Surface Runoff Calculations

As has been mentioned all of the main streams in Khartoum state with the exception of the Nile system are ungauged, and therefore an estimate has to be made to estimate the effects of storm water quality on the Nile system water quality. The Soil Conservation Service (SCS) method is appropriate for heavy rain events, and for dry climate conditions, and can be used in the Sudan and Khartoum state specifically. Using K=0.2 and appropriate CN number with respect to land use and soil classification, the excess rainfall P_e is determined in mm/month as [5]:

$$P_e = \frac{(P - KS)^2}{(P + (1-K)S)} \quad (3)$$

Where P is the total (cumulative) precipitation and S is land use parameter related to the Curve number (CN) which is a function of land use and soil classification.

The obtained estimate for a typical ungauged stream was selected and its runoff was estimated using two other methods. the SCS method yielded 3.71 compared to 16 using Hydrocad software [8] and 9.99 Mm^3 using the design hydrograph method [5]. Obviously the SCS is a very conservative estimate.

The estimated runoff from four rainfall events selected for sampling during 2006 rainy season is presented in Table 1 below.

Table 1: The estimated runoff Volume from the four rainfall events selected for sampling during 2006 rainy season.

Event Number	Event date	Mean state I (mm)	V (m^3)
1	24/ 8	5	337505.56
2	2-3/9	10	9662230.9
3	10/9	25	48311154.0
4	19-20/9	55	106284540.0

4.3 Storm Water Pollution Load

Table 2 clearly shows that early storms (August versus September) make the greatest pollutant concentrations due to absence of surface cleaning during the dry period. In addition it shows the stunning numbers of the total loads of pollutants in storm water.

Table 3 shows the percent contribution of each land use in the state to the total load. Obviously residential and agricultural are contributing most of the BOD, COD, Nitrate while phosphorous, nitrate and ammonia are manly contributed to from agricultural and open rural areas due to animal breeding and agricultural activities.

The insignificant contribution to total loading from industrial areas is due to its small area but not to reduced pollutant concentration. This fact leads to the conclusion that the environmental management of Khartoum state should focus now on residential and agricultural areas and take into consideration the future expansion of industrial areas.

4.4 Surface accumulation rates

Pollutant buildup on impervious surfaces is affected by many factors [9] such as population density, land use type, meteorological conditions, antecedent dry period, street and roof surface type and conditions, effectiveness of street cleaning and environmental management, and available sources of pollution which, in turn, include; atmospheric pollution, dry and wet fallouts (deposition), vehicle emissions, buildings and roads conditions, animals, urban debris and litter, spills and leaks.

The literature is wealthy with models describing build up of pollutants on the surface and pollutants washout by storm water [2, 9, 10-13]. In this study, build up of pollutants on the surface can be assumed to be linearly proportional to the area for certain types of land use and can be represented as [2]:

$$\frac{dm_s^p}{dt} = aA \qquad (4)$$

Where

$m_s^p =$ mass of pollutants on the surface (kg)

$a =$ surface accumulation rate constant (kg/ha.d)

$A =$ catchment area (ha)

$t =$ time since last rainfall event or street cleaning

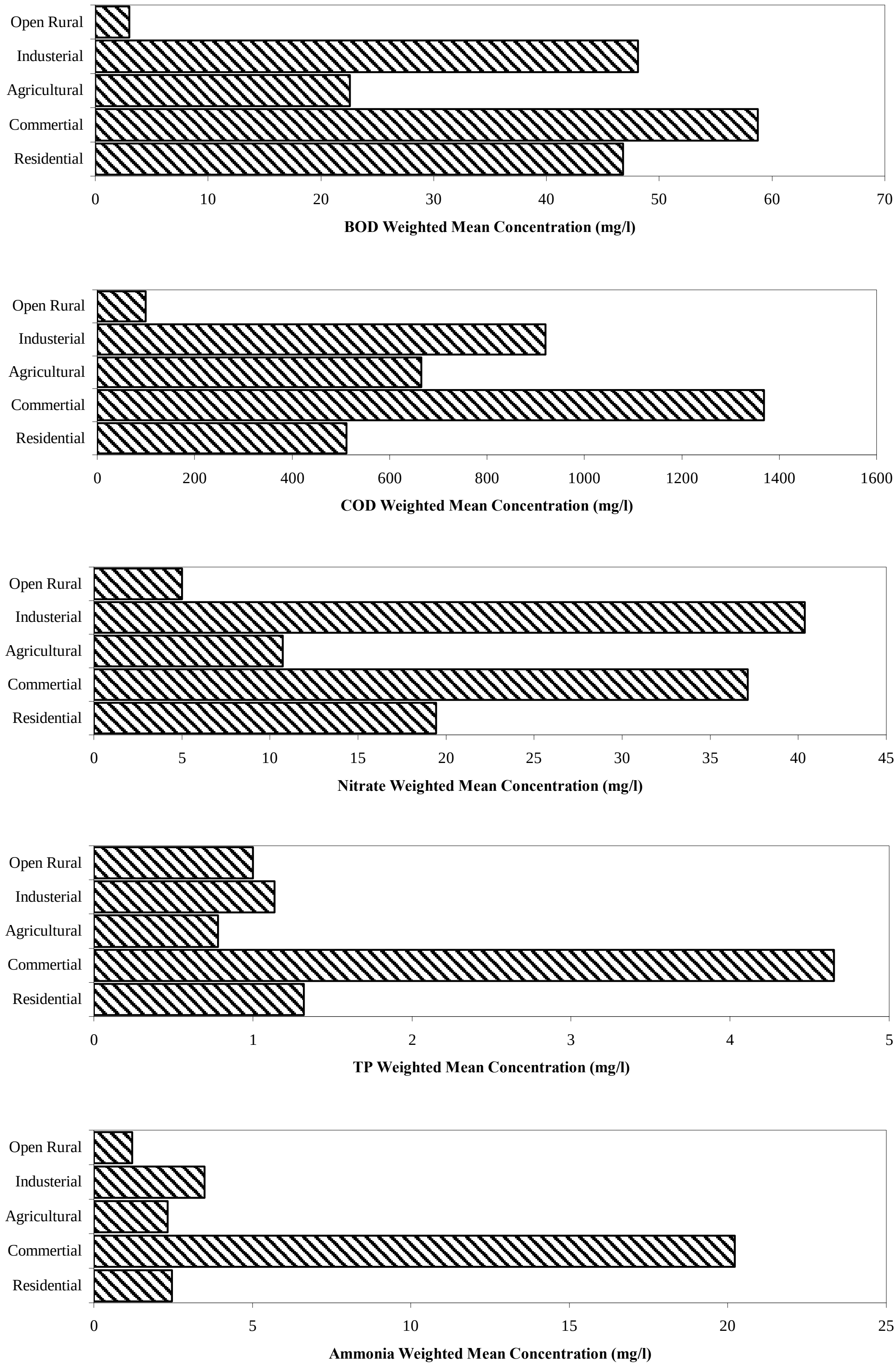
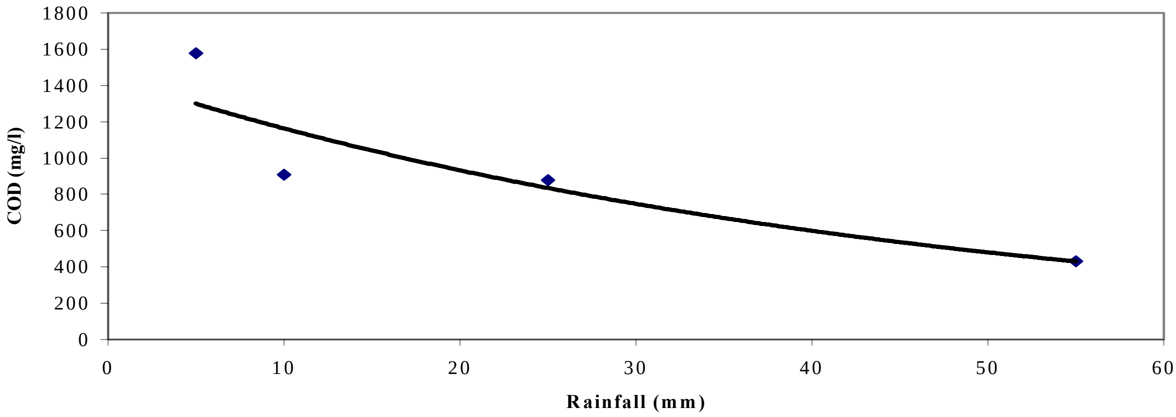


Figure 2: Weighted Event Mean Concentrations of Various Pollutants from Different Land Uses



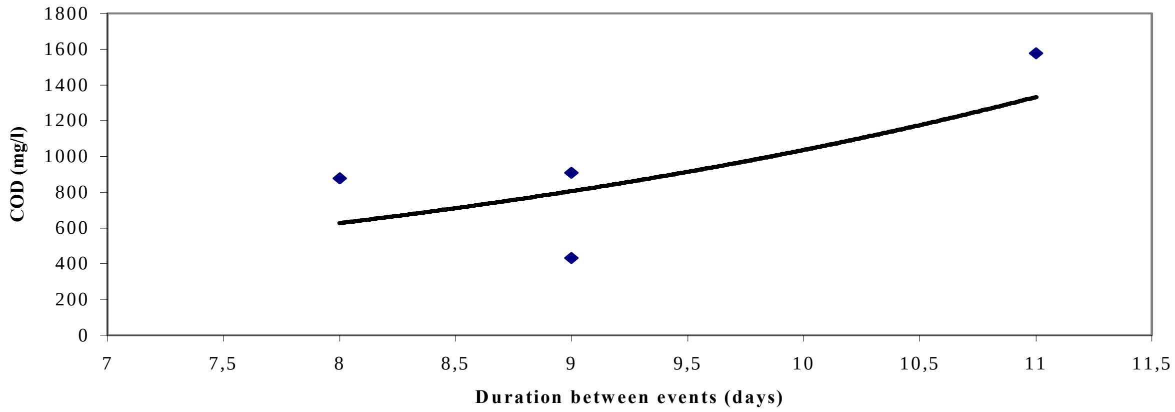


Figure 3: The variation of mean weighted COD concentrations with total rainfall depth and duration between events.

Table 2: Monthly Storm Water Quality Average Concentrations and Weighted Mean Concentration, and Total 2006 Season Loading.

Item	**BOD**	**COD**	**Nitrate**	**T.Phosphorus**	**Ammonia**
August Mean Concentration (mg/l)	62.48	1576.54	20.45	1.23	11.49
September Mean Concentration (mg/l)	45.79	854.27	33.45	2.94	14.11
Weighted Mean Concentration (mg/l)	48.20	757.30	23.70	2.20	14.11
Total Season Loading (tons)	7640	143301	5532	485	2339

Table 3: Percent Contribution of each Land Use in the State to the Total Storm Water Pollutant Loading (2006).

Land Use	% Area	% Contribution to Total Loading				
		BOD	COD	Nitrate	T.Phosphorus	Ammonia
Residential	17.8	0.45	0.24	0.35	0.23	0.21
Commertial	1.5	0.05	0.05	0.05	0.07	0.14
Agricultural	34.1	0.42	0.59	0.37	0.26	0.38
Industerial	0.1	0.00	0.00	0.00	0.00	0.00
Open Rural	46.6	0.08	0.12	0.23	0.45	0.27

When removal of pollutants is considered as a first order reaction, the following equation can be written

$$\frac{dm_s^p}{dt} = aA - bm_s^p \qquad (5)$$

Where $b =$ removal constant (d^{-1})

The case in Khartoum state is that the most pollutant removal mechanism is the washout since other mechanisms such as street cleaning and removal by re-suspension into the atmosphere are negligible. If the second term in Equation (5) is considered to be the washout by storm water, then the washout can be represented as

$$W = \frac{dm_s^p}{dt} = -bm_s^p \qquad (6)$$

and,

$$m_s^p = m_s^p\big|_{t=0} e^{-bt} \qquad (7)$$

Table 4 lists the four sampling rain events together with their dates, rainfall amount and mean weighted concentrations. The washout was calculated using Table 4 and Table 1, as the multiplication of the mean weighted concentration and the total runoff volume. Equations (6) and (7) were used to estimate the initial pollutant mass present on the surfaces of Khartoum state by fitting as shown in Figure 4. A summary of the model fit results are shown in Table 5.

As Table 5 indicates, the removal constant 'b' values are very low especially when compared to 0.2-0.4 d-1 from a US medium density residential area indicating that little cleaning if no cleaning practices are conducted at all [9].

After the fitting and estimation of the initial pollutants mass $\left(m_s^p\big|_{t=0}\right)$ and the removal rate 'b', the pollutant accumulation rates 'a' were calculated assuming a 10 month dry period for the 2006 rainy season (October 2005 to August 2006). The initial mass was divided by the dry period and then divided by the state area to find 'a'. Table 6

From Equation 5, the equilibrium mass present on the surfaces of the state can be calculated as (a/b). Table 7 lists the equilibrium masses of various pollutants for different land uses and the overall state average equilibrium mass.

The low values of 'b' listed in Table 5 indicate that, for example, the BOD surface load needs 52 days of continuous rainfall to fall to its equilibrium value calculated using Equation 7. of course this is not possible under the common meteorological conditions of Khartoum state, leading us to consider possible environmental control measures to achieve minimum pollutant coverage on Khartoum state surfaces. However, according to the pollution loading potential and the storm water quality data presented in Figure 2, land use in Khartoum state can be classified into three types

1. Land not in need of control such as the open rural
2. Lands sometimes needing control measures such as agricultural
3. Lands typically requiring control measures; typically some residential, commercial and industrial areas foreseeable in the near future.

5. Conclusions

Although the work done in this research is carried out for one season (2006) but its results are strongly conclusive of the following:

- The current environmental management practices of waste collection and land use designation in the Khartoum state are not keeping pace with the urban sprawl needs and are leading to a major contribution to the water quality deterioration.
- Major attention should be given to the current environmental practices in residential and agricultural areas and meanwhile pay attention to unplanned expansion in industrial areas.
- There have to be a storm water management and quality control measures to reduce the impacts on receiving waters (Nile system)
- More investigation and long term studies are needed to add accuracy and precision to this work and to create Decision Support Tools (DST) to reasonably

foresee the corrective actions control measures needed to mitigate the impacts of storm runoff from urbanized areas along the Nile system banks.

Acknowledgements

The authors would like to acknowledge the assistance of the Sanitary Laboratory assistant Samar Fath El Rahman in the measurement of sample pollutant concentrations.

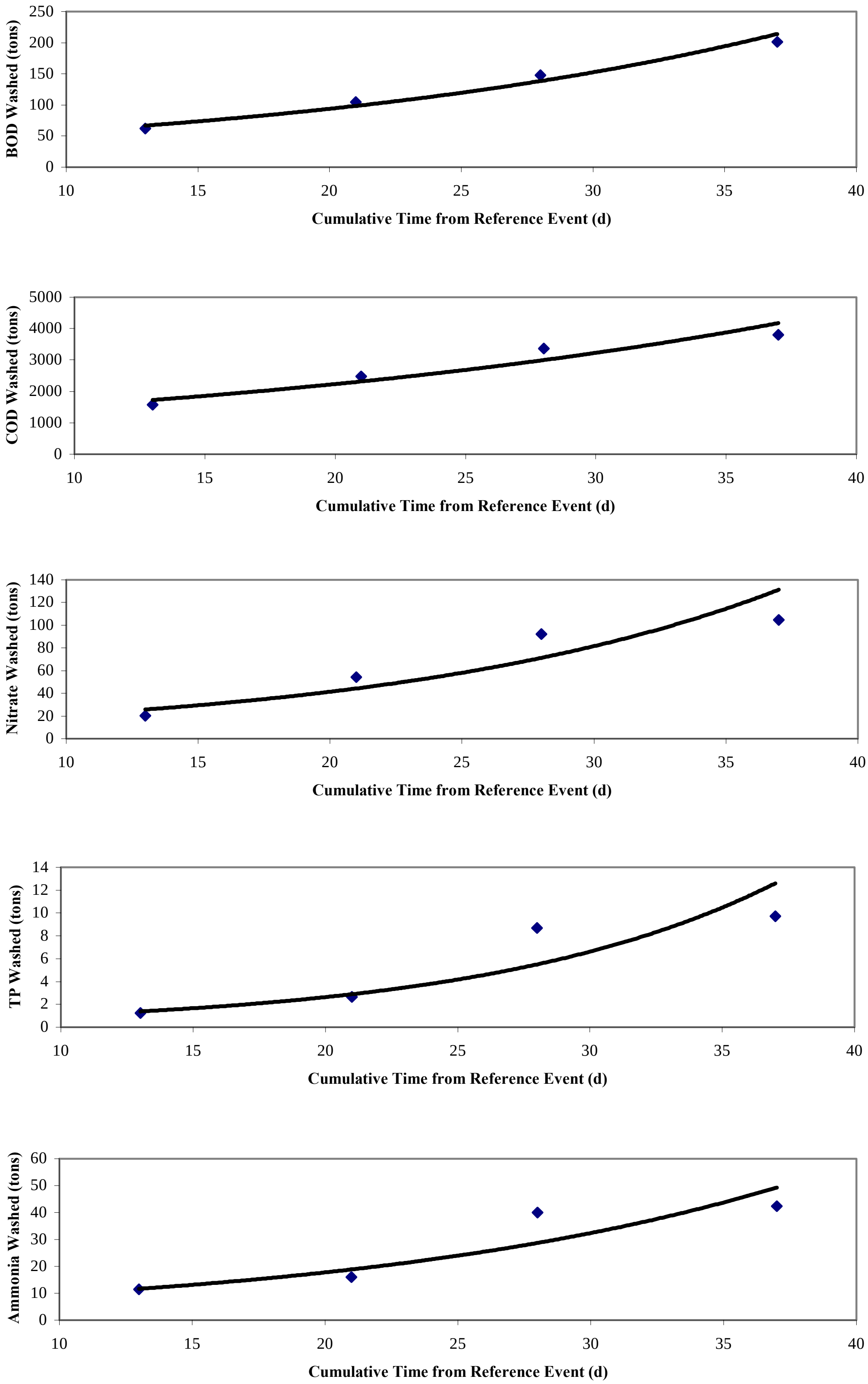


Figure 4: Estimated Pollutants Wash from Khartoum State Surfaces vs. Time from Reference Event (August 11th 2006).

Table 4: Mean weighted event concentrations of Khartoum State for different Pollutants per Event (2006)

Event Number	Event date	BOD mg/l	COD mg/l	Nitrate mg/l	T.Phosphorus mg/l	Ammonia mg/l
1	24/8	62.48	1576.54	20.45	1.23	11.49
2	2-3/9	42.16	907.26	33.65	1.42	4.47
3	10/9	43.43	877.98	37.94	6.04	24.04
4	19-20/9	53.02	432.02	12.50	1.03	2.41

Table 5: Model Fitting results

Parameter	BOD	COD	Nitrate	T.Phosphorus	Ammonia
$m_s^p\big\|_{t=0}$ (tons)	35.501	1068.8	10.65	0.4188	5.3245
B (d-1)	0.0486	0.0368	0.0679	0.092	0.0602
r2	0.9779	0.923	0.8727	0.8993	0.8758

Table 6: Estimated Pollutant Loading rates for different land uses and for the State

Land Use Type	Pollutants Accumulation rates 'a' (g/km^2/d)				
	BOD	COD	Nitrate	T.Phosphorus	Ammonia
Residential	13.76837	215.603417	3.136237	0.0809333	0.95124
Commertial	17.28169	576.457928	5.992223	0.2852794	7.786217
Agricultural	6.634899	280.167514	1.728526	0.0478242	0.896786
Industerial	14.14642	387.350723	6.515213	0.0696454	1.346483
Open Rural	0.88238	41.782491	0.806645	0.0613131	0.466914
Overall 'a' (g/km^2.d)	5.378939	161.939394	1.613636	0.0634545	0.806742

Table 7: Equilibrium mass on the catchment (a/b)

Land Use Type	Equilibrium mass on the catchment 'a/b' (g/km^2)				
	BOD	COD	Nitrate	T.Phosphorus	Ammonia
Residential	283.2998	5858.7885	46.18906	0.8797094	15.80133
Commertial	355.5903	15664.618	88.25071	3.1008626	129.3392
Agricultural	136.5206	7613.2477	25.45694	0.5198283	14.89678
Industerial	291.0786	10525.835	95.95306	0.7570149	22.36683
Open Rural	18.15596	1135.3938	11.8799	0.6664465	7.756054
overall 'a/b' (g/km^2)	110.6778	4400.5270	23.76489	0.6897233	13.40104

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