Water Quality Factors of Storm Runoff at Two Watersheds in Saudi Arabia: A Comparative Evaluation

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Abstract

Urban storm runoff can contribute to a variety of water quality problems. In this study, the qualitative and quantitative comparison of urban runoff of two arid urban areas was investigated. Data was recorded at two watersheds in Saudi Arabia, namely Dhahran and Abha and considered as the representative area for the arid zone. The main goal was to resolve the main factors in the process of suspended solids generation in urban storm runoff that would enable the development of a physically based model. Mean, extreme and aggregate values of the measured characteristics were determined for each accepted event. Correlation between each two of these event representatives were analyzed for both catchments. The trends among rainfall, overland flow, and quality characteristics within a storm event were observed. The first-flush effect of suspended solids was also studied. A correlation was established between event aggregate load of suspended solid and event aggregate runoff volume. It was observed that the more intense events carry more solids than less intense storm subject to the same storm volume. A positive trend was found between suspended solid load and the overland flow. The first-flush was found to have predominant effect more in Dhahran than in Abha.

Keywords: Urban Runoff, Arid Zone, Storm Runoff

Introduction

Stormwater usually refers to situations where the rainfall significantly exceeds the capacity of the vegetation and soil to adsorb it, and the excess moves under the influence of gravity.

For the past 30 years there has been increasing attention and concern focused on the quality of storm water that runs off impervious surfaces in urban environments, and what effect that runoff has on receiving water bodies and their associated biota. The Nationwide Urban Runoff Program (NURP) studies conducted in the early 80’s highlighted what many water quality experts had suspected for some time: urban runoff quality is extremely variable, there are many sources of urban runoff contamination, and urban storm water is extremely difficult to manage and control (U.S. EPA, 1983).

Although characterizing contaminants in storm water is a complex problem due to spatial and temporal variations in climate and weather conditions and the variable precipitation, it has become an increasingly important environmental issue for urban communities. Storm water runoff typically contains significant amounts of anthropogenic pollutants as well as naturally occurring materials such as sediments from soil erosion (Weibel et al., 1964). The early runoff in a storm event is often more contaminated than the later part of runoff, which may be due to several factors, including the mobilization of material accumulated during antecedent dry periods, a lack of dilution flow and a disproportionate runoff volume from the impervious surfaces, where pollutants may accumulate. The first flush phenomenon can be described as the initial period of storm water runoff during which the concentration of pollutants are substantially higher than those in the later stages of the storm event (Lee, et al., 2004). Characteristics of the first flush are influenced by a number of factors including intensity and duration of the rainfall event, catchment size, catchment land usage and antecedent rainfall. Previous studies have shown that the first flush phenomenon is a leading cause of degradation to the quality of the receiving waters (Lee, et al., 2004).

Urban storm runoff can contribute to a variety of water quality problems. These include direct pollution of receiving waters, impairment of water treatment processes due to extreme fluctuations in raw intake water quality, and reduction of sewer system efficiency. The pollution load of urban storm runoff is significantly higher than from secondary domestic sewage effluent (Sartor and Boyd 1972; Sartor et al. 1974; Cordery 1977). Urban storm water runoff is considered to be second in significance only to discharge from agricultural lands (“Clear” 1994), emphasizing the importance of understanding urban runoff processes to mitigate negative environmental impacts (“Guide” 1995).

Pollutants generated by urban land uses can be classified as floatable, sediment, nutrients, oxygen demand, oil and grease, heavy metals, toxic chemicals and bacteria. Deterministic rainfall-runoff models, which calculate runoff rate and volume over time, have been around for many years and are routinely used effectively to design hydraulic structures to convey storm water runoff. In contrast, the history of pollutant transport modeling is relatively brief.

Popular models, such as SWMM, NPS, MOSQITO and FLUPOL, generally use more or less physically based approaches to consider some or all of the phases in the pollution generation and runoff process.

The modeling of the rainfall-runoff process is essentially a homogeneous fluid mechanics problem primarily dependent on rainfall rate. Pollutant entrainment and transport involves the interaction of atmospheric deposition processes (availability); chemical and physical interactions between water and soluble, insoluble, and sorbable solids and miscible and immiscible fluids (mobilization); hydrodynamic interactions between turbulent water flow and settle able solids (transport); and chemistry (mobilization and transformation). The complexity of these interactions precludes analytical solutions, leaving full-scale experiments to determine useful relationships, factors, and formulas to be used in numerically based models.

This paper describes the results of a monitoring program for storm water runoff in two areas of the Kingdom of Saudi Arabia namely Dhahran and Abha.

This study documents the existence of strong first flush for almost all storms and most water quality parameters. The data used in this study is based on a project funded by KACST titled, “Water harvesting of urban storm runoff in Saudi Arabia” (Ishaq and Khararjian, 1987).

Methodologies

1. Catchment descriptions

Dhahran watershed (Figure 1) is partially situated in the northwestern part of campus of King Fahd University of Petroleum & Minerals and extends in the northeastern part of the Arabian Oil Company (Saudi Aramco) in Dhahran, Saudi Arabia. All the residence halls of the university and their supporting facilities are situated within this watershed. The area of the watershed is 1.817 km^2 and is divided into nine sub catchments. Street and parking lot slopes range from one to four percent. A total of 0.521 km^2 were judged to contribute to the runoff hydrograph including 0.29 km^2 of the paved area, 0.159 km^2 of the supplementary paved area, and 0.045 km^2 of the grassed area. The rest of the watershed has no runoff producing potential for the rainfall intensities prevailing in the Dhahran area.

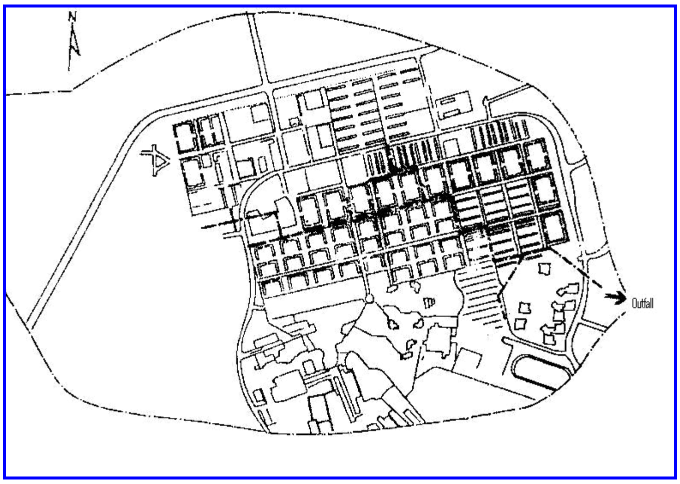

Figure 1: A sketch of Dhahran watershed

Abha is a city in southwestern Saudi Arabia. Abha lies 80 km east of the Red Sea and 850 km southwest of Riyadh, the national capital. The storm drainage system in Abha (Figure 2) for this study was chosen from a developing area near the valley of the wadi Abha. The drainage network was divided into thee parts. The first part was a 431 m long, 1.1 m diameter AC pipe with a slope of 3.5% draining the uppermost part of the catchment. The middle section is 320 m long earthen channel with a slope of 4.2%. The final section is 626 m long, 2.5 m wide RC culvert with an average slope of 1.7%. This system runs through a large extent of open land and has three sub catchments. The runoff from this area is primarily from streets and hill slopes whose gradients range from 5 to 12%. The total drainage area of this system is 0.206 km2, of which 0.083 km2is judged to contribute to the runoff hydrograph including 0.051 km2 of paved are, 0.034 km2 of supplementary paved area, and 0.011 km2 of grassed area.

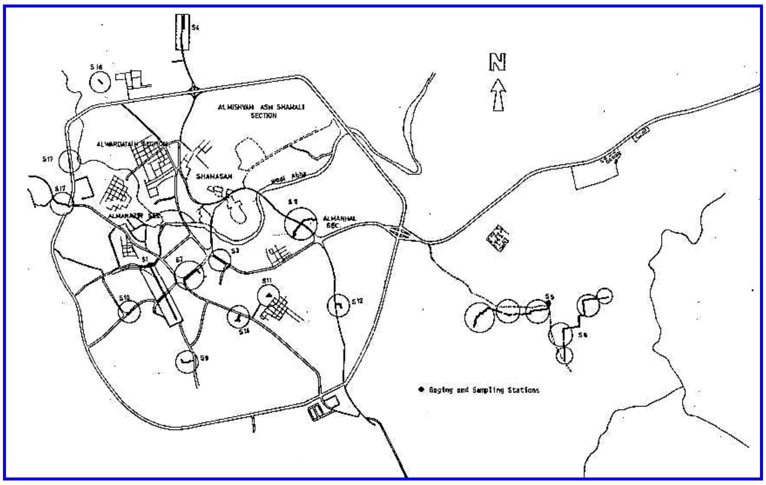

Figure 2: A sketch of Abha watershed

2. Data collection

The study period for Dhahran was from 1984 to 1986 and 12 significant storms on this watershed was observed. For Abha, the study period was from 1985 to 1986 and the number of significant storm was 7. Table 1 and Table 2 show the significant storm event characteristics for Dhahran and Abha watershed.

Table 1: Storm event characteristics in Dhahran watershed

Sl No.	Storm Event	Antecedent Period (Day)	SS_{mean} (mg/l)	Total Rainfall (mm)	Event max intensity I^+ (mm/min)	Event max flow Q^+ (m^3/s)
1	February 28, 1984	0	113	12.70	0.053	0.426
2	March 19, 1984	19	1205	12.70	0.297	1.769
3	March 20, 1984	1	106	10.20	0.042	0.248
4	March 22, 1984	2	51	3.00	0.021	0.215
5	December 10, 1984	259	167	3.80	0.064	0.149
6	December 28, 1984	18	63	7.60	0.021	0.119
7	November 5, 1985	338	6169	26.70	0.423	0.125
8	December 4, 1985	29	615	30.50	0.191	0.550
9	December 21, 1985	17	114	3.80	0.085	0.125
10	January 30, 1986	39	182	2.50	0.067	0.011
11	February 6, 1986	*7*	*327*	2.50	0.088	0.068
12	April 21, 1986	45	1619	32.50	0.833	1.400

Table 2: Storm event characteristics in Abha watershed

Sl No.	Storm Event	Antecedent Period (Day)	SS_{mean} (mg/l)	Total Rainfall (mm)	Event max intensity I^+ (mm/min)	Event max flow Q^+ (m^3/s)
1	May 16, 1985	0	98	10.40	0.583	0.020
2	July 3, 1985	47	287	6.80	0.050	0.030
3	July 17, 1985	14	66	10.20	0.833	0.004
4	March 2, 1986	225	1921	51.20	0.330	0.062
5	April 7, 1986	35	3326	32.20	0.650	0.920
6	April 9, 1986	2	3210	29.00	0.967	0.167
7	September 6, 1986	147	352	14.20	0.050	0.053

During the study period, some climatic differences between the two catchments were found which are represented in Table 3. It can be seen from Table 3 that event maximum rainfall intensity, I^+, is usually higher at Abha catchment than that of Dhahran and also the event duration, *D*, is longer at Abha than in Dhahran. On the other hand event mean Suspended Solid concentration, SS_{mean} was higher at Dhahran than Abha. This is especially true in the early rainy season and whenever there is long gap between storms. During the 1985 rainy season in Dhahran watershed, the November 5 storm which was the first of the season, carried suspended solid of 6169 mg/l (Table 1); as the season progressed, the concentration subsided to lower levels ranging from 114 mg/l for the storm of December 21, 1985 to 1619 mg/l for the storm of April 21, 1986. Similar phenomenon was observed for Abha also (Table 2). Prior to occurrence of the storm of March 2, 1986 a long antecedent period is observed; the consequence is large quantity of suspended solid in the storm of April 7, 1986.

Table 3: Comparison of Event characteristics between Dhahran and Abha

Event Characteristics	Dhahran	Abha
Catchment Mean Event Duration *D* (min)	260	385.71
Catchment mean rainfall, *P* (mm)	12.38	22
Range of Rainfall, *P* (mm)	2.5-32.5	6.8-51.2
Catchment mean rainfall Intensity, I^+ (mm/min)	0.2	0.495
Range of Catchment rainfall intensity, I^+ (mm/min)	0.021-0.833	0.05-0.967
Aggregate mass of suspended solid, M_{ss} (g/m^2)	0.03-22.02	0.11-60.3
Mean suspended solid concentration, SS_{mean} (mg/l)	51-6169	66-3326

3. Runoff Quality Model

As a first step toward the development of a physically based storm runoff quality model, statistical analyses of the data were undertaken. The main goal was to resolve the main factors in the process of suspended solids generation in urban storm runoff that would enable the development of a physically based model. No attempt to develop universal statistical relationship was made. Mean, extreme and aggregate values of the measured characteristics were determined for each accepted event. Correlation between each two of these event representatives were analyzed for both catchments. The trends among rainfall, overland flow, and quality characteristics within a storm event were observed. The first-flush effect of suspended solids was also studied.

Results and Discussion

1 Correlation between Event Characteristics

The event representatives of water quality characteristics were plotted against event representatives of rainfall and overland flow (Figure 3 and Figure 4). For this purpose, suspended solid was selected as quality parameter. This was done for each catchment, bearing in mind that water quality should depend on rainfall and overland flow.

Figures 3 and 4 show that the event loads of suspended solids per unit area M_{ss} (aggregate mass of suspended solids collected during an event from 1 m^2), correlates to aggregate volume of storm runoff per unit area V_w (aggregate volume of storm water collected during an event from 1 m^2).

The coefficient of the linear regression between V_w and M_{ss} found for Dhahran was 1.2189, which is smaller than that calculated for Abha, 2.3279. This indicates that the Abha catchment is more loaded with solids than that of Dhahran.

The linear regression presented here show that this type of equation could not be transferred from one catchment to another without recalibration and *Mss* could not be predicted reliably using only event aggregate runoff volume obtained as follows:

Dhahran:

$$M_{ss}\ (\text{gm/ m}^2) = 1.2189 \times V_w\ (\text{L/ m}^2),\ R = 0.89$$

Abha:

$$Mss\ (\text{gm/ m}^2) = 2.3279 \times V_w\ (\text{L/ m}^2),\ R = 0.93$$

As stated earlier, the objective of this analysis was not to find exact relationship among the factors in the process of suspended solids generation in urban storm runoff, but to determine whether a correlation exists. Correlation Coefficient R was calculated between the chosen pairs of factors to find possible linear correlation. The values are presented in the Table 4 and Table 5.

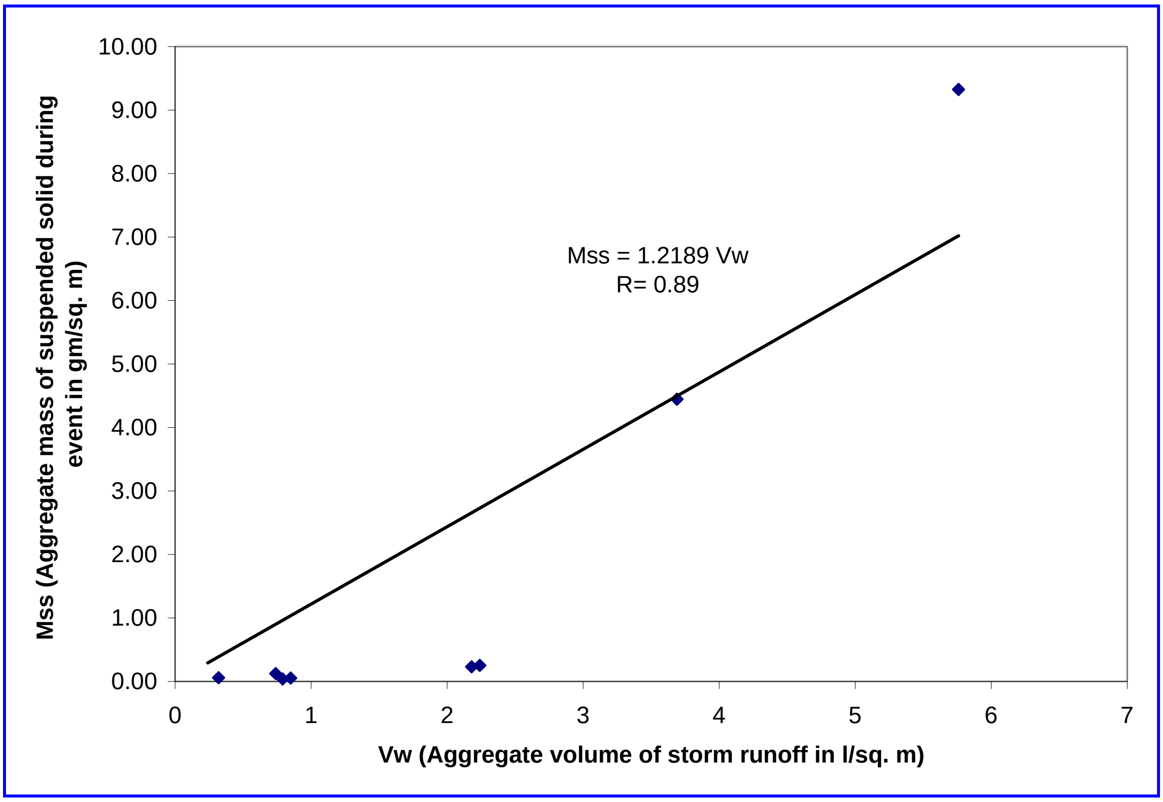

Figure 3**:** Aggregate mass of suspended solid Aggregate volume of storm runoff for Dhahran

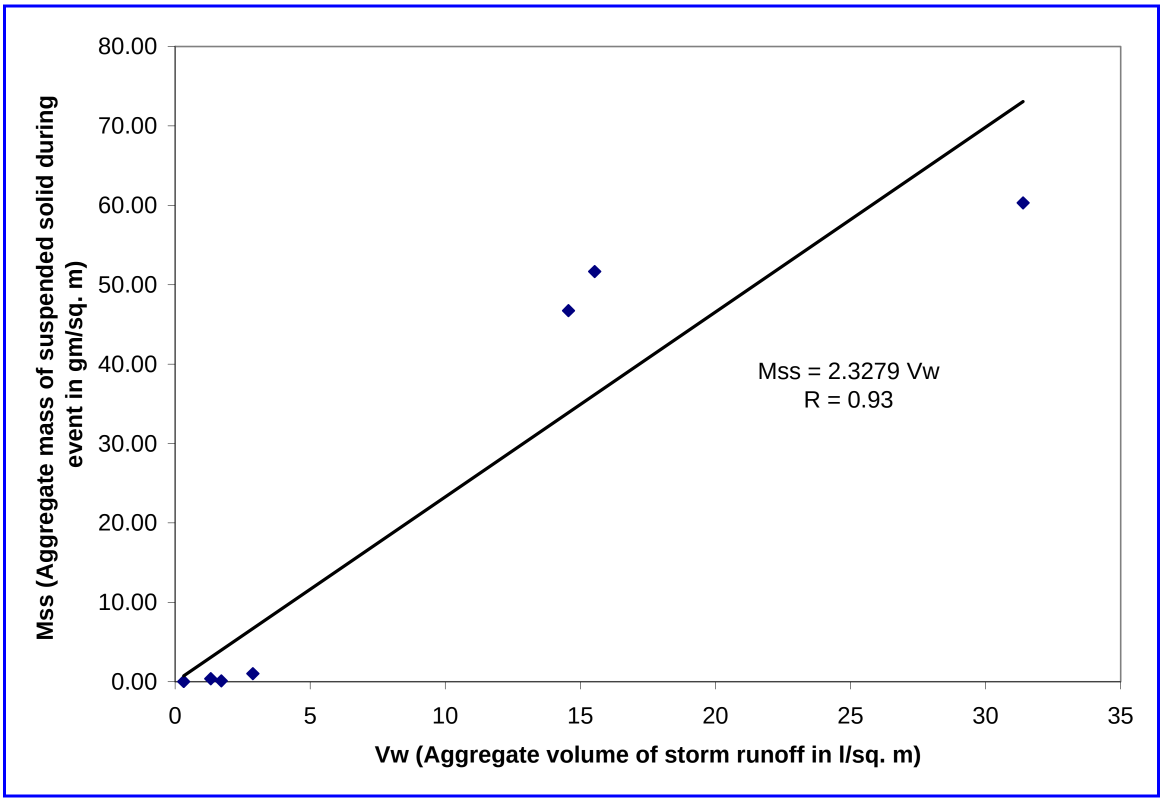

Figure 4**:** Aggregate mass of suspended solid Aggregate volume of storm runoff for Abha

Before measurements began, it was speculated that the intense rainfalls should carry more pollutant than less intense ones. This was endorsed by the correlation found between event mean suspended solids loading rate Qss_{mean} and event maximum rainfall intensity I^+ for Dhahran which was R=0.89 (Table 4), however, this trend was not observed in the Abha catchment (Table 5). A considerable correlation was found between Qss_{mean} and event maximum overland flow Q^+ for both catchment; which is R=0.96 for Dhahran and R=0.75 for Abha. Therefore it can be conferred that heavy rainfall events are more polluted than less intense ones. This also suggests that the kinetic energy of rain drops and the overland flow rate, which increase with rainfall intensity, play important roles in sediment entrainment.

Table 4: Correlation Coefficient between pairs of Event characteristics (Rainfall P, Maximum rainfall intensity I^+, Volume of storm runoff V_w, Mass of Suspended solid M_{ss}, Mean suspended solid loading rate Qss_{mean}, Maximum overland flow Q^+) in Dhahran

Variable	P	I^+	V_w	M_{ss}	Qss_{mean}	Q^+
P	1.00	0.75	0.93	0.79	0.65	0.62
I^+	0.75	1.00	0.83	0.98	0.89	0.76
V_w	0.93	0.83	1.00	0.89	0.83	0.83
M_{ss}	0.79	0.98	0.89	1.00	0.95	0.85
Qss_{mean}	0.65	0.89	0.83	0.95	1.00	0.96
Q^+	0.62	0.76	0.83	0.85	0.96	1.00

Table 5: Correlation Coefficient between pairs of Event characteristics (Rainfall P, Maximum rainfall intensity I^+, Volume of storm runoff V_w, Mass of Suspended solid M_{ss}, Mean suspended solid loading rate Qss_{mean}, Maximum overland flow Q^+) in Abha

Variable	P	I^+	V_w	M_{ss}	Qss_{mean}	Q^+
P	1.00	0.15	0.99	0.94	0.69	0.35
I^+	0.15	1.00	0.11	0.32	0.50	0.25
V_w	0.99	0.11	1.00	0.93	0.65	0.29
M_{ss}	0.94	0.32	0.93	1.00	0.88	0.54
Qss_{mean}	0.69	0.50	0.65	0.88	1.00	0.75
Q^+	0.35	0.25	0.29	0.54	0.75	1.00

2 First Flush Effect of Suspended Solids

At the time wash off commences from an impervious surface, often a large quantity of loosely attached materials exists on that surface. These loosely bound and easily transported materials are usually incorporated largely into the initial part of the storm flow. The first flush effect concentrates pollutant loads in the first part of the storm water. Based on this assumption, the first part of a storm is sometimes diverted to a treatment plant together with domestic sanitary water. However, the findings of a study in tempered zone, where 197 selected events were analyzed from several catchments (Saget, 1995), indicate that the first flush phenomenon is not always present. Thus, the design criteria based on the first flush effect, at-least from the point of view of the processes of the surface that involve small diameter particles, could undergo significant reconsiderations.

A more useful way to observe the First Flush phenomenon has been reported by Griffin et al., 1980. A plot of cumulative flow (x-axis) versus cumulative load (y-axis) produced for a single event. In this plot *no-flush line* is drawn at 45 degree with x-axis and going through the origin. If the plotted data are above the *no-flush line*, then first flush has occurred, because for a given fraction of the total flow, a greater fraction of the total load has been generated.

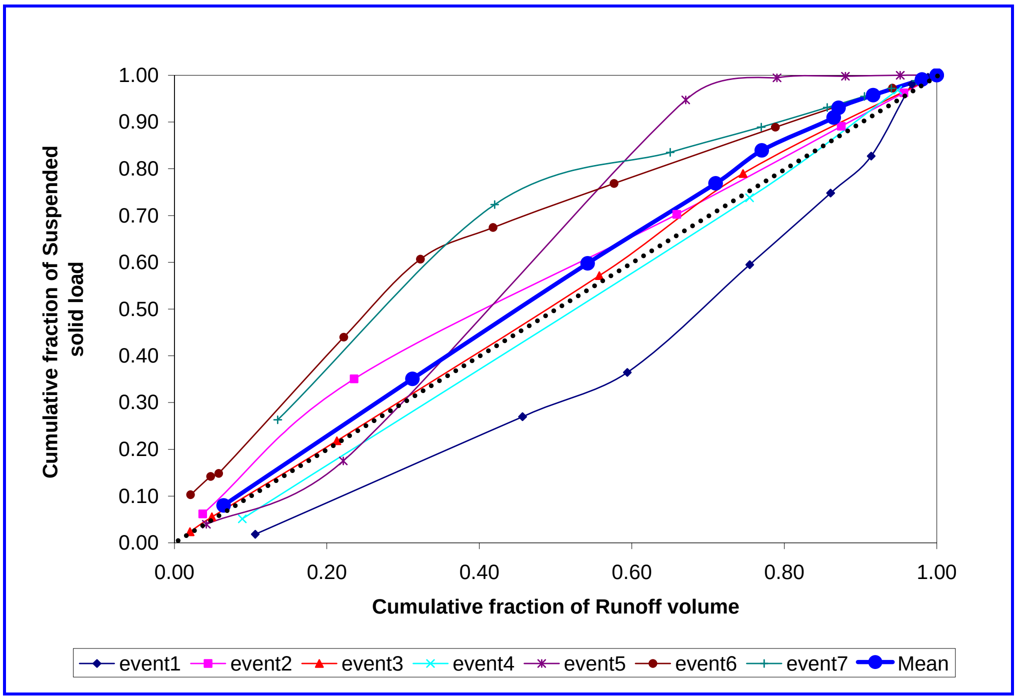

Figure 5: First Flush effect in Dhahran

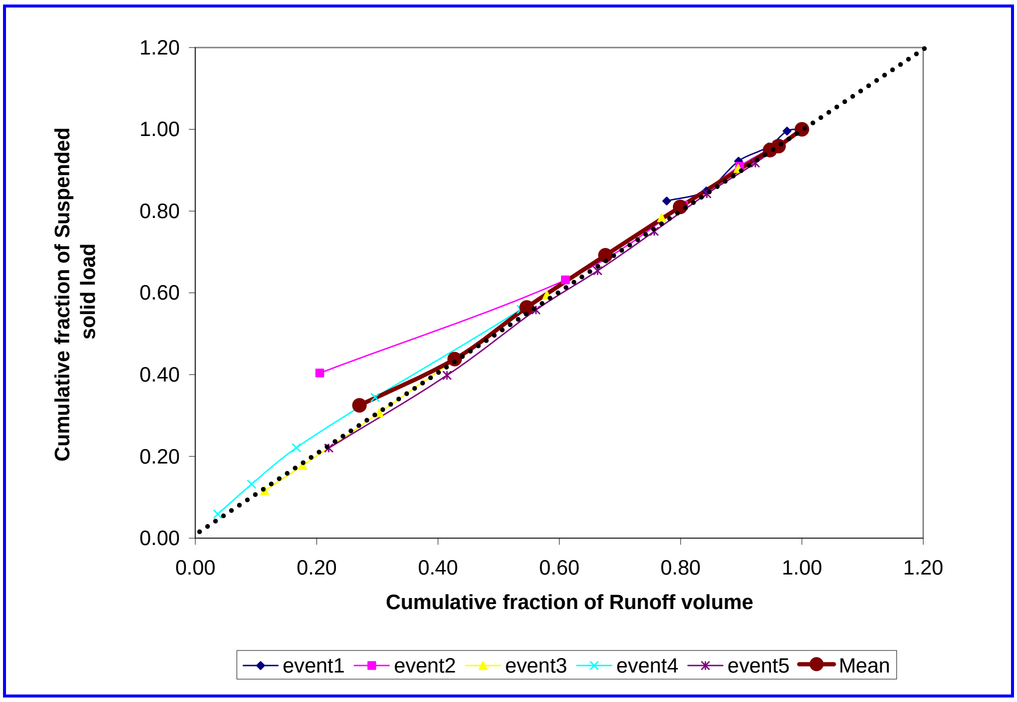

Figure 6: First Flush effect in Abha

Investigation was made to find whether first flush effect was present during the storms in Dhahran and Abha catchment. For this purpose, suspended solid cumulative load curves (mass curve) were constructed for both the catchment. It is seen from figures 7 and 8 that the mean values are above the 45 degree *no-flush* line. So it can be concluded that there is a trend of first flush in both the catchment and it has more effect on Dhahran catchment than Abha.

Conclusions

The following general conclusions can be drawn:

- Event aggregate load of suspended solid is correlated to the event aggregate runoff volume.
- It was observed that the more intense events carry more solids than less intense storm subject to the same storm volume.
- A positive trend was found between suspended solid load and the overland flow and the suspended solid load depends on the rainfall intensity as well.
- The first flush effect of suspended solids was observed in both the catchment. It had more effect in Dhahran than Abha.

Acknowledgement

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Notation:
P = Rainfall
D = Event Duration
I^+ = Event maximum rainfall intensity
SS = Suspended Solid
M_{ss}= Aggregate mass of suspended solid during event per unit area
SS_{mean} = Mean suspended solid concentration
V_w = Aggregate volume of storm runoff per unit area
Q^+ = Event maximum overland flow
Qss_{mean} = Event mean suspended solids loading rate
AP = Antecedent Period

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