EFFICIENCY AND FLOW REGIME OF A HIGHWAY STORMWATER DETENTION POND IN WASHINGTON, USA

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Abstract. Wet detention ponds are a preferable alternative in treating stormwater runoff. Literature suggests that a detention pond's efficiency in removing principal pollutants of concern, TSS and metals, is highly variable and is affected by a complex array of factors including its geographic location. The objective of this paper was to investigate the TSS and metal removal efficiency of a highway stormwater detention pond in Spokane, Washington along with its flow regime. Pond influent and effluent data for TSS and metal were collected for approximately two years. TSS removal by the pond was found to be 68.1–99.4% with an average of 83.9%. Average metal removal efficiency was 54.7–64.6% which is 72.5–86.9% of the TSS removal. The pond's flow regime was found to vary with its changing surface topography, a result of sedimentation of suspended solids.

Keywords: suspended solids, metal, removal efficiencies, wet detention pond, stormwater runoff

1. Introduction

Highway stormwater runoff constituents of primary concern include total suspended solids (TSS) and heavy metals such as Cd, Cr, Cu, Ni, Pb, and Zn (Gupta *et al.*, 1981; Kobriger and Geinopolos, 1984; Hares and Ward, 1999). These pollutants are recognized as nonpoint-source pollutants and can be a threat to the receiving water ecosystems (Pettersson, 1997; Wu *et al.*, 1998). Detention ponds have been found to be cost-effective means of improving the water quality of stormwater runoff (Wu *et al.*, 1996; Mallin *et al.*, 2002). There are three types of detention ponds: wet, dry, and dual-purpose. Among these three types of detention ponds, wet ponds are generally preferable based on their enhanced performance in removing TSS (Comings *et al.*, 2000).

Removal of pollutants in a detention pond is considered to be a function of its residence time (Walker, 1998). Pettersson (1998) reported a TSS removal of 14–82%, maximum Zn removal of 74%, and a Pb removal of 10–82% based on a pilot study of a detention pond in Jarnbrott, Sweden. He also reported that the pollutant removal capacity was greatly influenced by the antecedent dry periods for each storm event. The pond's sediment and associated pollutant removal efficiencies are also influenced by influent particle size distribution (Greb and Bannerman, 1997). A study of pollutant removal by a detention pond in Greenville, N.C. showed median pond treatment efficiencies (PTEs) of 71% for TSS, 45% for particulate organic carbon (POC) and particulate nitrogen (PN), 33% for particulate phosphorus (PP), and 26–55% for metals (Stanley, 1996). A combined probabilistic-deterministic simulation of a detention pond located in a mining area of Raleigh County, West Virginia, indicated that pond designs seldom met the regulatory requirements for sediment concentration on a daily or monthly basis, even though they may comply with annual sediment yield requirements (Tiyamani *et al.*, 1994).

Therefore, it can be concluded that the ability of a wet detention pond to remove suspended solids and heavy metals is highly variable. The variability can be a function of pollutant concentration in the runoff, traffic volume, storm duration and its intensity, time between storms, seasonality, and surrounding land uses (Barrett *et al.*, 1998; Field *et al.*, 1998). In addition, removal efficiencies of detention ponds also depend to a large extent on the flow regime within the pond and their geographic locations. The objective of the paper is to present the data pertaining to suspended solids removal, metals removal, and flow regime for a pond in Spokane, Washington. Data presented and its interpretation should aid the practicing engineers to effectively design a wet detention pond.

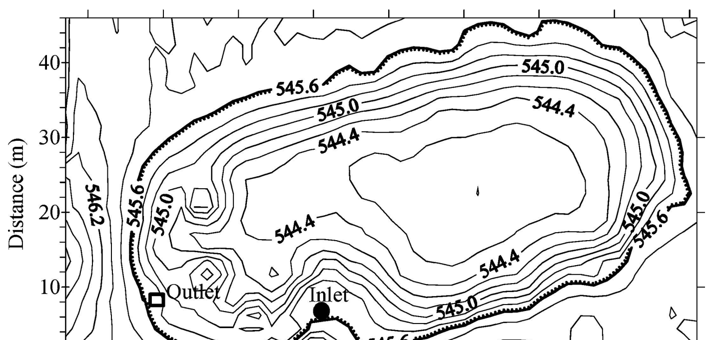
2. Site Description

The Spokane pond is located near the interchange of Interstate 90 and Highway 195, as shown in Figure 1a, and was constructed in the fall of 1993. It receives stormwater runoff from approximately 1.6 km of eastbound and westbound lanes of Interstate 90 with average daily traffic (ADT) of 49,400 vehicles and their associated unpaved medians and shoulders (Yonge *et al.*, 2002). The pond's drainage area consisted of approximately 10 ha of pavement and 6.4 ha of pervious land. The pond's full-pool volume, surface area, and average depth were 1857 m^3, 2378 m^2, and 0.9 m, respectively. The inlet structure was a 0.9 m diameter concrete pipe at a slope of 2.9% (Coombs, 1998). The outlet structure was a 0.6×1.2 m flat rectangular grate at an elevation of 545.71 m above mean sea level (MSL). Water entered through the grate into a drop structure, and was then conveyed away from the pond via a 0.45 m diameter corrugated metal pipe. A contour map of the pond with inlet and outlet locations is presented in Figure 1b. Spokane, WA had an average annual rainfall of 42 cm with the wet season occurring during the winter and spring months. The pond had a permanent pool of water all year round.

3. Data Collection

A large volume of data was collected over a period of approximately two years. American Sigma 960 flow meters and American Sigma 900 portable samplers

(a)



(b)

Figure 1. (a) Approximate location of the wet pond. (b) Contour map of the Spokane, Washington wet pond showing the inlet and the outlet locations.

were used for monitoring flow and collecting samples, respectively. Flow, pH, and conductivity were monitored for both the influent stream and the effluent stream from the ponds. Rainfall data was monitored by using Sigma Model 2149 tipping bucket rain gauge. Monitored data were recorded at 2-minutes intervals and were downloaded remotely using a cell phone-modem system and Sigma Insight remote connection software. During a rainfall event, pond influent and effluent samples were collected automatically based on predetermined set points of sample initiation and sampling frequency. Three times during the summer, samples of algae were also collected from the pond to determine the potential for metal uptake.

4. Laboratory Methods

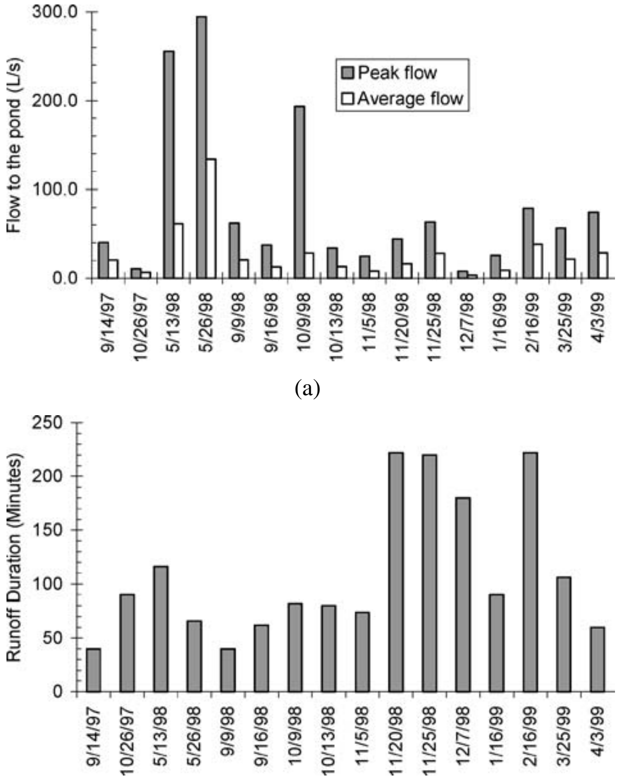
Aqueous phase samples were collected and stored according to the procedures specified in *Standard Methods for the Analysis of Water and Wastewater*. Total solids were analyzed by drying at 103–105 °C according to the method 2540D described in the *Standard Methods*. *Total* metals were analyzed according to USEPA Method 200.8. The acid extracts resulting from this procedure were stored at 4 °C prior to Inductively Coupled Plasma Mass Spectrometer (ICP-MS) analysis in 50 mL Nalgene bottles. The ICP-MS method detection limits (MDLs) were 0.759 μg/L for Cu, 2.856 μg/L for Zn, 0.181 μg/L for Cd, and 0.327 μg/L for Pb. The MDLs were determined by applying a statistical analysis to ICP-MS data generated from replicate blank samples and replicate spike samples that covered a range of concentrations (Berthoux and Brown, 1994).

5. Results and Discussion

Seven full complements of inlet and outlet metal and suspended solid data were collected for the duration of the project. Event mean concentration (EMC) was used to estimate the pollutant loads in the influent and the effluent flow streams. An EMC value represents a flow averaged concentration computed as the total pollutant load divided by the total runoff volume and is computed by employing the following equation.

$$\mathrm{EMC} = \bar{C} = \frac{M}{V} = \frac{\int_0^t c(t)q(t)\,\mathrm{d}t}{\int_0^t q(t)\,\mathrm{d}t}$$

where M is the total mass of constituent over the event duration; V is the total volume of water generated during the flow event; $\bar{C}$ is the flow weighted average concentration for the entire event; $c(t)$ is the time varying pollutant concentration; $q(t)$ is the time varying flow; and t is the time.



(a)

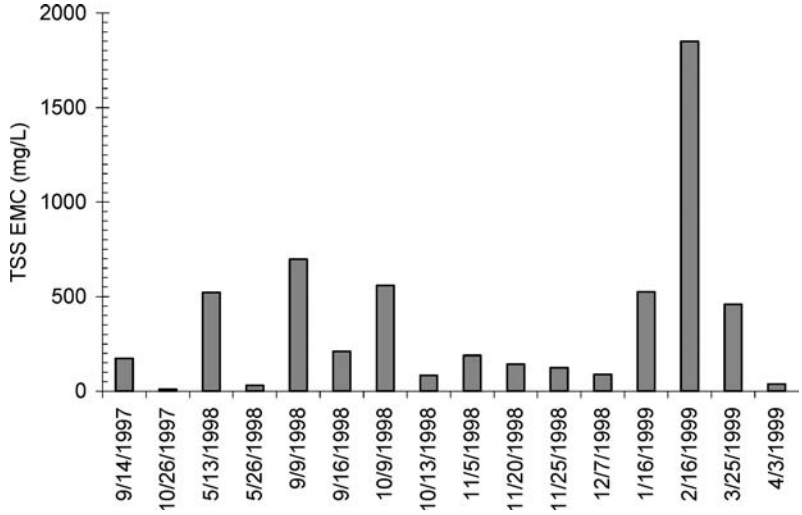
(b)

Figure 2. (a) Peak and average flow to the detention pond. (b) Duration of flow to the pond.

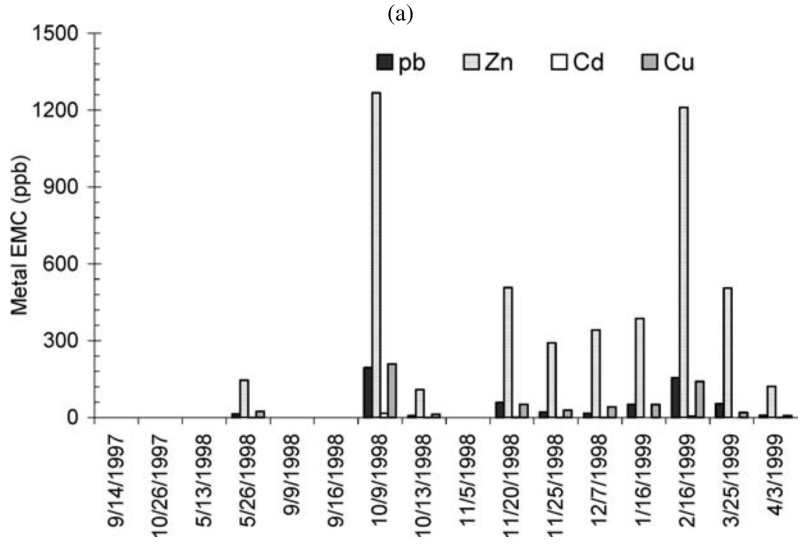
5.1. Influent to the pond

Figure 2a presents peak and average flows, in liters per second (L/s), to the detention pond as a function of storm dates. An examination of the figure reveals that higher flows to the pond are during two storms in May 98. The two storms in May 98, however, have smaller durations resulting in significantly smaller average runoffs. Peak flows to the pond ranges from approximately 7.9–294.5 L/s with the average flow range as 3.4–133.8 L/s. Duration of the runoff ranges from 40–222 minutes (min). Most of the longer duration storms occurred during the wet season. Runoff duration as a function of storm date is presented in Figure 2b.

EMCs of TSS in the influent to the pond are plotted in Figure 3a as a function of the storm date. The range is 9.6–1850.0 mg/L. Largest TSS loading occurred during the storm event on February 16, 99. Figure 3b presents EMCs of the metals of concern – Cd, Cu, Pb, and Zn. Cd concentration was often below detection limit. The range is observed to be 0.0–16.0 ppb. EMCs of Cu range from 7–209 mg/L with the highest concentration occurring during the storm event on October 9, 98.



(a)



(b)

Figure 3. (a) TSS concentrations as a function of time. (b) Metal concentrations as a function of time.

May 13, 98 storm generated a runoff hydrograph, to the pond, of longer duration and higher peak flow than that of October 9, 98 storm. Yet the EMC of Cu for this storm is much smaller, 24.0 ppb. EMCs of Pb range from 7.0–194.0 mg/L with the highest occurring on October 9, 98. EMCs of Zn range from 108.0–1267.0 ppb with the highest concentration again occurring during the storm of October 9, 98. As with Cu, EMCs of Pb and Zn are found to be much smaller for the longer duration and higher peak runoff hydrograph on May 13, 98.

The temporal variability in runoff flow and EMCs of TSS and metals of concern, therefore, appear to be quite unpredictable. The unpredictability is due to the fact that flow and pollutant concentrations to a detention pond are defined by a complex array of factors including storm intensity, storm duration, interval between storms, highway traffic volume, highway maintenance practices, conditions prior to a storm, and surrounding land use.

5.2. TSS REMOVAL EFFICIENCY

Figure 4 presents TSS removal efficiency for the storm events that had complete set of inlet and outlet concentration data. Removal efficiency was computed as the ratio of the removal of TSS by the pond to its influent concentration. Removal by the pond was estimated by subtracting the EMC of TSS for the effluent from that of the influent. A negative efficiency of 6% is observed for May 26, 98 storm. The negative removal efficiency may be attributed to dense algal growth observed during the summer months. It was observed that algae from the pond escaped into the effluent stream and was collected by the sampler. Further, the influent and effluent TSS concentration were around 32 mg/L which is small. Therefore, the negative removal efficiency can be excluded from further analysis.

The exclusion of the negative value results in a removal efficiency range of 68.1–99.4% with an average of 83.9% and a standard deviation of 11.8%. Therefore, statistically a TSS removal efficiency of 72.1–95.7% can be expected.

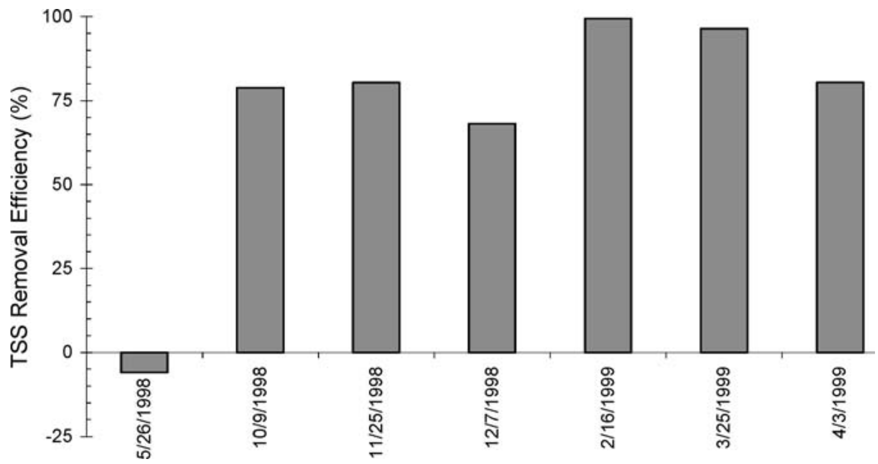


Figure 4. TSS removal efficiency for different storm events.

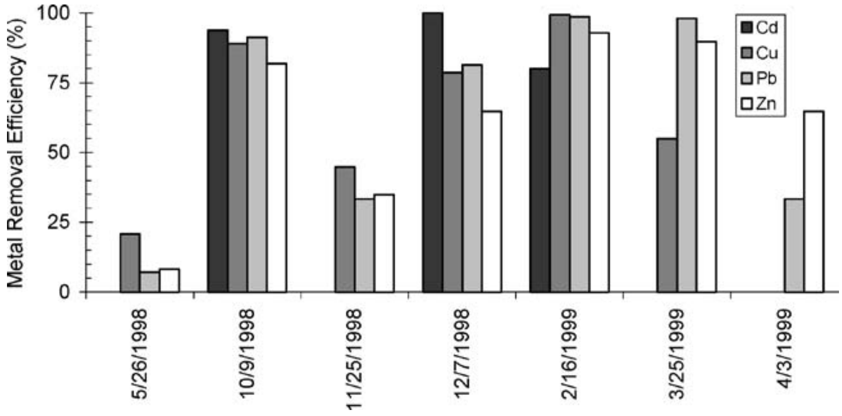


Figure 5. Metal removal efficiency for different storm events.

5.3. Metal removal efficiency

Metal removal efficiencies, computed as the ratio of the metal removal by the pond to its influent concentration, for the different storm events are plotted in Figure 5. Removal efficiencies were calculated for the *total metal* consisting of both the particulate and the dissolved fractions.

For the reported storms, *total* Cd removal efficiency ranges from 0–100% with an arithmetic mean of 54.7%. *Total* Cu removal efficiency is 20.8–99.3% with a mean of 64.6%. Removal efficiency ranges for *total* Pb and Zn are 7.1–98.7% and 8.2–92.8%, respectively. The corresponding mean is 63.3% and 62.4%, respectively. It was observed that the smaller removal efficiencies are associated with smaller influent metal concentrations. It is possible that for small influent metal concentrations, algae in the effluent can significantly alter the removal efficiency.

Therefore, *total metal* removal efficiency of the pond is quite variable. However, it is to be noted that effluent Cd concentration was frequently below the MDL i.e., less than 0.181 μg/L. Further, effluent concentration of Cu, Pb, and Zn were all below the Washington state surface water standard.

5.4. Metal removal vs. solids removal

Transport and removal processes of metals in a wet pond environment can be very complex. Partitioning is the most important process that affects the overall removal of metals in a pond. TSS is one of the parameters among many that may influence the partitioning of metals onto solids (Glenn and Sansolne, 2002). Consequently, metal removal efficiency may be considered a function of solids removal efficiencies.

Total metal removal was correlated, by employing the method of linear regression, with solids removal and in the process May 26, 98 data was not used for the fact that negative TSS removal efficiency was due to the algae that escaped from the pond. It was found that *total* Cu removal efficiency was 72.5%, *total* lead removal efficiency was 86.9% and *total* zinc removal was 85.5% of the pond's TSS removal efficiency with the correlation coefficients varying from 0.58–0.87. The correlation coefficient was computed to be the square root of the variance that is indicative of the data spread.

Therefore, *total* metal removal efficiency of the pond is 72.5–86.9% of the TSS removal efficiencies with a moderate correlation coefficient range of 0.58–0.87.

5.5. The pond's flow regime

The flow regime of the pond was investigated by constructing a model and subjecting it to a number of tracer tests as described by Coombs (1998). The objective of the tracer test was to evaluate the effect of changing geometry of the pond bed, due to sedimentation, on its flow regime. Tracer test results were analyzed by employing the technique proposed by Rebhun and Argaman (1965).

Flow regime was characterized by hydraulic residence time and dead volume. Hydraulic residence time is the average time for which a fluid particle stays inside the pond and is computed to be the ratio of the effective volume, volume available for storage of the incoming flow, of the pond to its influent volumetric flow rate. Theoretical residence time is taken to be the ratio of the total pond volume to the influent volumetric flow rate and is based on the assumption that the entire volume is available for storage of the inflow. Dead volume is defined as portions of the pond that does not mix with the incoming flow and as a result reduces effective volume. Inflow to and outflow from dead volume are very small.

Tracer test results revealed that the actual residence time of the model pond representing the field conditions, as depicted in Figure 1b, was 64% of the theoretical residence time, a result of approximately 38% of dead volume. Short circuiting due to the close proximity of the outlet of the pond to its inlet might be considered a contributing factor to such short residence time. Tracer tests were also done by placing baffles near the inlet to deflect the incoming flow away from the direct path to the outlet. When a short baffle was placed near the inlet at an angle of 60 degrees, dead volume was found to decrease to 6% with a longer actual residence time which was 79% of the theoretical value. A study with a submerged inlet was also found to provide an improvement in the flow regime. Actual residence time was 75% of its theoretical value and the dead volume was approximately 29%. Therefore, placement of a baffle near the inlet at 60 degrees or a submerged inlet can improve the hydraulic regime and consequently, the efficiency of the pond in removing TSS and metal.

6. Conclusions

Flow and pollutant concentrations to a detention pond are defined by a complex array of factors including storm intensity, storm duration, interval between storms, highway traffic volume, highway maintenance practices, conditions prior to a storm, and surrounding land use. Consequently, efficiency of the pond in removing TSS and metals was found to be highly variable. TSS removal was found to be 68.1–99.4%. *Total* metal removal was approximately found to be 72.5–86.9% of the TSS removal. The changing flow regime in the pond due to its changing surface configuration can be considered a significant factor to add to the variability of its removal efficiency.

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