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UNCERTAINTY OF SEDIMENT LOAD PREDICTION AT A DETENTION POND BASED ON MONTE CARLO SIMULATION

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Sediment accumulation in detention ponds has adverse effects on the intended uses of the pond. Higher volume and depth of sediment can cause flooding when storm events occur and can cause the operational failure of pond. Monte Carlo simulation is used to predict sediment loads and depth of accumulation at the Ledang Heights pond in Nusajaya, Johor. The simulation results show the maximum occurrence for observed sediment loads was 0.0062 tons (16.51%). While the maximum occurrence of sediment depth was 0.0005 mm (17.53%). Prediction analysis for 100 years by the MUSLE and trap efficiency methods showed linear increments of sediment loads and depth with time. Monte Carlo simulation gave the maximum probability of occurrence for predicted sediment loads and depth. By elucidating risk associated with the sediment load and depth, rational decision making for the most practical operation of detention pond can be achieved.

INTRODUCTION

Recent years have seen an increase in the number of wetlands and detention ponds designed and constructed for the treatment of storm-water (Farm, 2002). Detention ponds have been used for quite some time now for management of storm water. These ponds, originally designed for reducing peak flows during heavy storm events, also play an important role in improving the water quality of storm runoff, especially reducing the contamination and sediment.

Sediment eroded from disturbed urbanized areas (Senior et al., 2003) and soil materials are transported by surface runoff and deposited in wetlands and detention ponds. Heal et al. (2006) stated that sediment accumulates in detention ponds and wetlands over time due to several chemical, physical and biological processes. These include sediment production, sediment transportation rate, sediment type, mode of sediment deposition, detention operation and design, and streamflow variability. Predicting the sediment coming into a detention pond, its deposition and its accumulation through the years has been an important problem in hydraulic engineering (Salas and Shin, 1999).

Continued accumulation of sediments may lead to the deterioration of water quality and the migration of pollutants through sediments. Routine removal of accumulated sediments may be necessary to minimize the risk of contamination and maximize the operational efficiency of the pond. The frequency of removal and the handling of accumulated sediments require a full understanding of both the quantity and quality of these sediments. This study assessed the probabilities related to sediment accumulation load and depth that may effect the operation of a detention pond.

The objectives of this study were:

i. To analyze the uncertainties and risk of sediment load and depth over 10 and 100 year periods using Monte Carlo simulation combining the normal distribution.

ii. To forecast accumulated sediment loads and depth from the MUSLE and trap efficiency methods.

iii. To examine the relationship between forecasted sediment loads and depth from both approaches.

LITERATURE REVIEW

Sedimentation embodies the processes of erosion, entrainment, transportation, deposition and the compaction of sediment. These are natural processes that have been active throughout geological times and have shaped the present landscape of our world. The principle external dynamic agents of sedimentation are water, wind, gravity and ice. Although each may be important locally, only the hydrospheric forces of rainfall, runoff, streamflow and wind forces are considered. Many of our rivers, lakes and oceans have been contaminated by pollutants derived from sedimentation processes.

The deposition of sediments can reduce pond storage capacity. In estimating detention sedimentation and sediment accumulation, either by empirical or analytical approaches, a number of uncertainties exist (Salas and Shin, 1999). Empirical models, based on surveys and field observations, have been developed and applied to estimate annual reservoir sedimentation load, accumulated reservoir sedimentation load and accumulated reservoir sedimentation volume after a given number of years of reservoir operation (Strand and Pemberton 1982; Morris and Fan, 1998). Also mathematical models for predicting reservoir sedimentation based on equations of motion and continuity for water and sediment (Chen et al., 1978; Soares et al., 1982; Morris and Fan, 1998). There are several uncertainty analyses that have been developed and applied in water resources engineering, For an example uncertainty models such as first-order analysis (FOA) and Monte Carlo simulation (MCS) (Yen et al., 1986). Our analysis was carried out to achieve better management of water resources and the best practical operational design of a detention pond in our country.

METHODOLOGY

Site Description

This study was carried out at a detention pond in Ledang Heights, Nusajaya, Johor (Figure 1). It is located west of Johor Bahru, near the town of Gelang Patah. About 361 acres of residential area is currently under development with some housing phases already completed and launched. The detention pond was designed for the 100 year major storm and it is about 10 acres in area. It is used mainly for recreational activities. There is no hydrometric gauging station located at the pond. Therefore, rainfall data from 1998 until 2007 was obtained from Jabatan Pengairan dan Saliran (JPS), Johor Bahru, Johor. Incoming sediment inflow data was obtained from the site itself.

Data Collection

Data collection at the detention pond was conducted three times at five stations at the inlet of the pond and two stations at the outlet of the pond. Usually incoming sediment load into the detention pond is generally composed of suspended sediment and bed load. Flow discharge and suspended sediment data were collected at the site. A range of flow discharge measurement was carried out using the Swoffer 2100 (DID, 1976). Suspended sediment samples was collected at each stations using the DH 48 sampler with depth integrating technique (DID, 1977). There were two samples taken for each station at the inlet and three samples for each station at the outlet of the detention pond.

Laboratory Analysis

Total suspended solid (TSS) was measured at each station. The suspended sediment concentration obtained after sampling was filtered and dried at 103º – 105º C. Calculation of TSS is as follows:

$$\text{Total suspended solid (mg/L)} = \frac{(A-B)x1000}{C} \tag{1}$$

where A is weight of filter and residue in mg, B is weight of filter in mg and C is volume of sample filtered in mL. Conversion mg/L to tons/day was calculated by the following equation (DID, 1977):

$$\text{Suspended Sediment Rate, } Q_s \text{ (tons/day)} = P_m.S.q.86400\,.10^{-6} \tag{2}$$

where

$$P_m = \frac{P_S}{d_S - (Sx10^{-6})(d_S - d_W)} \text{ (tons/m}^3\text{)}$$

S = Total suspended solid (TSS) concentration (mg/L)

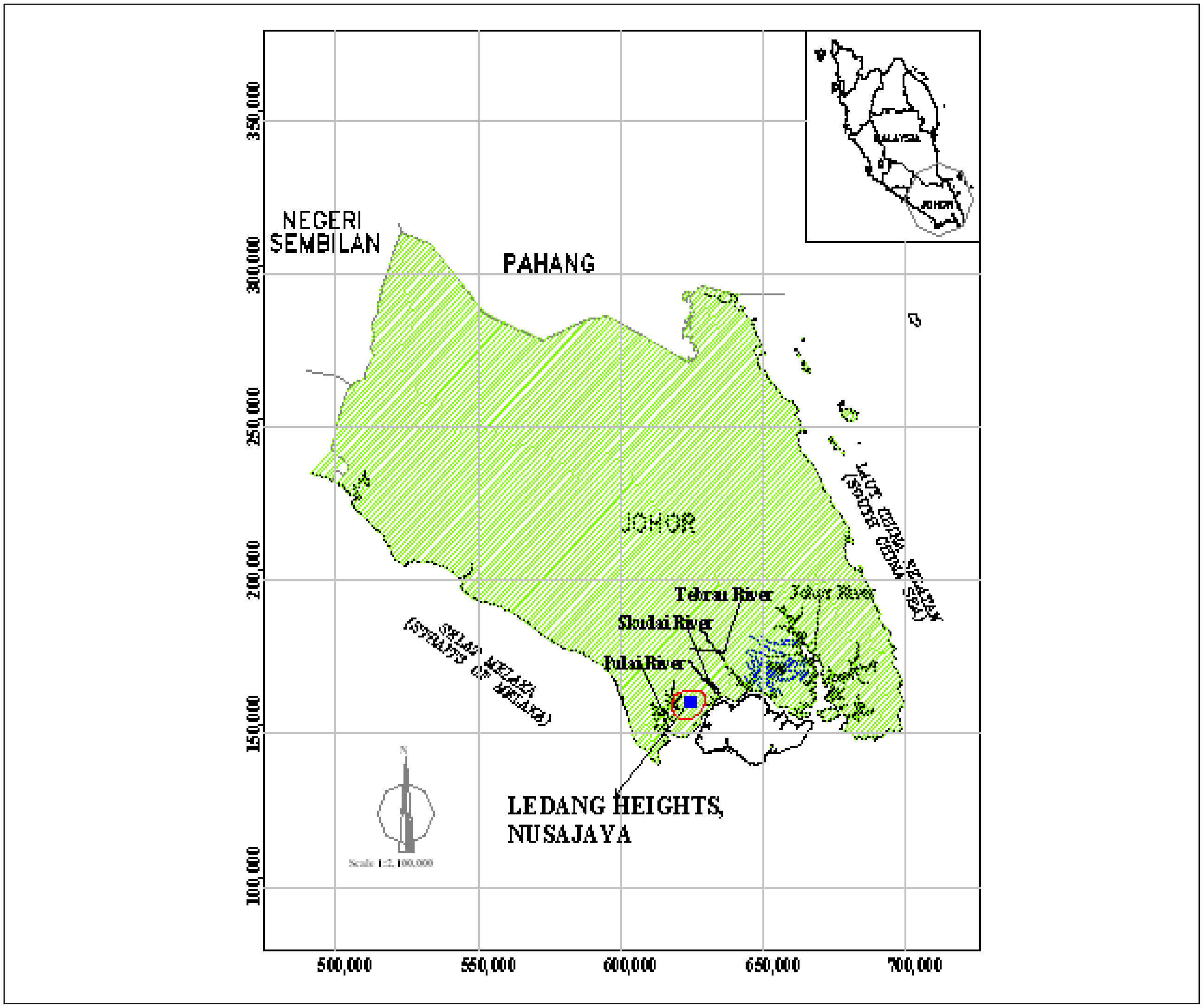

Figure 1. Location of Ledang Heights, Nusajaya, Johor.

q = Flow discharge (m^3/s)

P_s @ d_s = Bulk density of sediment = 2.65 ($tons/m^3$)

d_w = Bulk density of water = 1 ($tons/m^3$)

86400 = conversion factor from seconds to day unit

The accumulated sediment in detention pond can be obtained from suspended sediment rate by applying the conversion factor as shown in following equation (DID, 1977):

$$\text{Sediment depth, d (mm)} = Q_s.\frac{1}{P_S}.\frac{1}{A} \tag{3}$$

where

Q_s = suspended sediment rate (tons/day)

P_s = Bulk density of sediment (2.65 $tons/m^3$)

A = Surface area of detention pond (m^2)

Estimating Sediment Yield Using The MUSLE Equation

The Modified Universal Soil Loss Equation (MUSLE) was developed by the USDA Agricultural Research Service in order to estimate soil erosion rates (Williams, 1975). MUSLE was used to predict sediment erosion from individual storms by replacing the runoff energy in the USDA Universal Soil Loss Equation, with a rainfall term R under different types of land use or cover, such as forest, range land, crops, residential development, urban development, and so on. The MUSLE equation is:

$$Z = B\left(Qq_p\right)^{0.56} K \cdot LS \cdot CP \tag{4}$$

where

Z = Sediment yield (tons per event)

Q = Storm runoff volume (m^3)

q_p = Peak runoff rate (m^3/s)

K = Soil-Erodibility Factor

LS = Slope Length and Steepness or Gradient Factor

CP = Crop Management Factor and Erosion-Control-Practice Factor

B = 11.8 (converted for metric system if Q in m^3 and q_p in m^3/s)

Forecasting Sediment Loads and Sediment Depth

Trap Efficiency of Detention Pond

The trap efficiency, TE_f, of a detention pond is measured as the proportion of the sediment in the inflowing water and trapped in the pond. Mathematically, the trap efficiency of detention pond is:

$$TE_f = [\ (Load_{in} - Load_{out}) / Load_{in}\ ] \times 100 \tag{5}$$

where $Load_{in}$ and $Load_{out}$ are the total incoming and outgoing suspended sediment inflow obtained from the pond respectively. The trap efficiency is an important factor in the amount of sediment accumulation in detention pond over the design life and measured in percent unit. Then, the accumulation of total sediment load trapped in the detention pond in one year can be calculated as (Salas, 1999):

$$DSL = 3.65Q_s \times TE_f \tag{6}$$

where DSL is in tons and Q_s is the average suspended sediment rate in unit tons/day. By assuming the accumulation of sediment load in the detention pond is uniform and constant in each year, the accumulation of sediment load in the detention pond (in tons) for n years can be measured as follows:

$$DSL_n = DSL + 2DSL + 3DSL + \ldots\ldots + nDSL \tag{7}$$

Regression Analysis

The forecast function based on regression analysis can be used to predict new values on a least-squares linear regression of a range of known data or known x-arrays and y-arrays. Least-squares fit of a straight line to a graph of response variable versus one predictor variable is:

$$y = b_0 + b_1 x \tag{8}$$

where x is independent variable, y is dependent variable, b_1 is slope of the graph and b_o is the y-intercept. In this study, the regression analysis was carried out using results from MUSLE analysis where the dependent variables are sediment load and sediment depth being forecast using rainfall data from 1997-2007. The linear equation obtained was used to forecast the next 100 years data.

Monte Carlo Simulation

MCS or probability simulation is one of the techniques used to understand the impact of risk and uncertainty in forecasting models. For the purpose of this study, MCS is considered in term of estimating the ranges of values of sediment accumulated in the detention pond. MCS methods choose scenarios based on probability of occurrence of sediment accumulated, such that scenarios with a higher probability of occurrence are chosen as the most likely value estimated.

MCS is categorized as a sampling method because the inputs are randomly generated from probability distributions to simulate the process of sampling from an actual population. The data generated from the simulation can be represented as probability distributions or histograms. In addition, random distribution functions are needed to provide source values for running a MCS. In this study, the normal distribution was applied. The normal distribution was chosen because it is an easy method and needs only the mean, *ì* and standard deviation, *ó* to completely describe the distribution. The function of this normal distribution used for MCS is:

Normal Distribution in MCS = Normal Value (mean, standard deviation) (9)

RESULTS AND DISCUSSION

Flow Discharge and Suspended Sediment Rate

The analysis for a total of 30 samples at the inlet and 18 samples at the outlet was carried out using Equation 1. Each suspended sediment data from TSS experiment (mg/L) was converted into the rate unit, which is tons/day based on Equation 2. Then all the flow discharge data and TSS data was averaged. Table 1 shows the average value of flow discharge and suspended sediment rate measured on 20/May/2008, 27/May/2008 and 13/June/2008.

The relationship between the flow discharge and incoming sediment load or sediment rating curve is shown in Figure 2. This sediment rating curve would be applied for sediment load forecasting.

Trap Efficiency of Detention Pond

Based on the Equation 5, the trap efficiency of detention pond was calculated from the data collected (Table 2).

The trap efficiency obtained on 20/5/2008 was 50%, on 27/5/2008 was -650% and on 13/6/2008 was 33.3% (Table 2). The negative value calculated on 27/5/2008 showed the value of

Table 1. Average value of flow discharge and suspended sediment rate.

Date	Flow discharge, Q (m^3/s)		Suspended Sediment Rate, Qs (tons/day)	
	Inlet	Outlet	Inlet	Outlet
20/May/2008	0.006	0.013	0.012	0.006
27/May/2008	0.001	0.005	0.002	0.015
13/June/2008	0.002	0.008	0.003	0.002

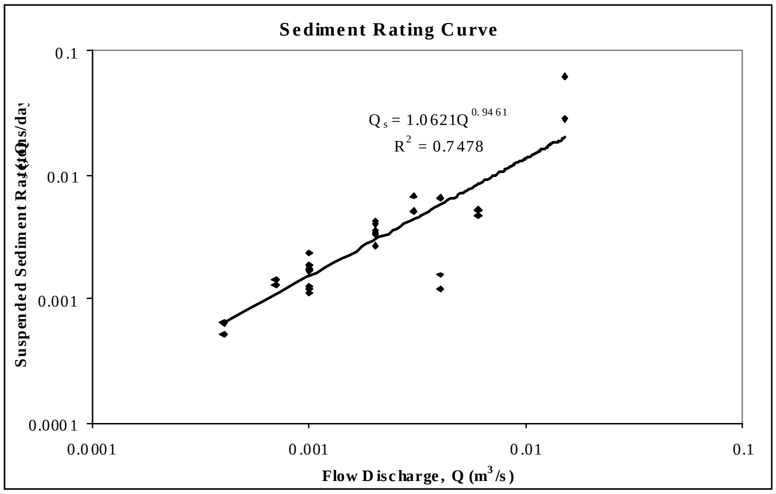

Figure 2. The sediment rating curve.

suspended sediment rate at the outlet was higher than the suspended sediment rate at the inlet. Rainfall which occurred on that day might have affected the retention time of detention pond. The suspended sediment also did not settle on the bed of pond. This negative value was neglected in this study. Therefore, the average value of the trap efficiency of detention pond on 20/5/2008 and 13/6/2008 was used in forecasting the accumulation sediment loads in the detention pond.

Forecasted Sediment Loads and Sediment Depth

Sediment load was estimated using the MUSLE method (Equation 4). The daily rainfall data for ten years duration (1998-2007) was obtained from the JPS, Johor Bahru to calculate the monthly and yearly rainfall depth, *P*. The fraction value of particle and size distribution at the site, the soil erodibility, *K* was assumed to be 0.25. The *LS* factor and *CP* factor used in this equation were 0.66 and 0.003 respectively. The sediment depth was calculated using Equation 3. Table 3 shows the accumulated sediment loads and sediment depth data obtained from the MUSLE equation. Figure 3 shows the linear regression equation for sediment loads and sediment depth.

A linear equation was obtained from this data. The sediment loads and sediment depth was regressed giving a coefficient R^2 of 0.938. The significant value of R^2 indicates a significant relationship between sediment loads and depth with time. The significant R^2 indicates that the sediment loads and sediment depth will increase with time. This linear equation was used to forecast the sediment loads and sediment depth for 100 years from 2008 until 2107.

The averaged trap efficiency, TE_f value from Equation 5, which was 41.7%, was used to predict the accumulated sediment load in the detention pond in one year. The sediment load accumulation was assumed uniform and constant for every year, therefore a linear multiplication of number of years was calculated in Equation 7. The sediment load was forecasted for the next 100 years duration from 2008 until 2107. Table 4 shows the predicted sediment loads and depth in the detention pond for the 100 years. The depth of the sediment accumulated in the pond can be measured by multiplying the accumulated sediment load with the area of the detention pond.

Figure 4 shows the predicted sediment loads and sediment depth for the 100 year duration. The average value for sediment loads calculated from the MUSLE and trap efficiency methods was 77 tons and 61 respectively. While the average value for sediment depth from MUSLE and trap efficiency method was 6 mm and 4.7 mm respectively. The percentage of difference between the average values for both approaches was 21.1%. In addition, the projection for both approaches showed that the percentage difference became less when the number of years was increased.

Table 3. Sediment loads and sediment depth data from MUSLE equation.

No. of Year	Year	Sediment Loads, Yi (tons)	Sediment Depth, d (mm)
1	1998	1.0119	0.0779
2	1999	1.2702	0.0978
3	2000	1.2702	0.0978
4	2001	1.6616	0.1280
5	2002	3.2301	0.2488
6	2003	5.4135	0.4169
7	2004	7.2430	0.5578
8	2005	8.5695	0.6600
9	2006	10.0800	0.7763
10	2007	12.2099	0.9403

Result of Monte Carlo Simulation Analysis

The simulation was run by using the mean and standard deviation value from the observed and predicted sediment loads and depth. The simulation started by entering the various numbers of trials to complete the simulation. Each simulation would produce a new value of mean and standard deviation. For normal distribution functions, the best bell shape of the normal curve obtained was be limited to a value of skewness of 0 and a kurtosis value of 3. The exact value of the skewness and kurtosis was not obtained because would take a longer time and observation to get the perfect bell shape. Therefore, in this study, the random number of trials and value of skewness and kurtosis was applied. Then, by referring to the value of skewness and kurtosis, the simulation was stopped.

Observed Sediment Loads and Sediment Depth

Table 5 below shows the actual value as the input and output summary from the MCS for observed data with the number of trials which gives the best shape of the normal distribution.

The most likely values would be observed from the simulation. These values can range from the fourth higher values between the histograms or probability density curve. These likely values represent the range of probability of sediment loads and sediment depth to occur within the study. These probability values can be shown in the probability density curve (Figure 5). The summary of results for estimating the probability of occurrence for the observed data is shown in Table 6.

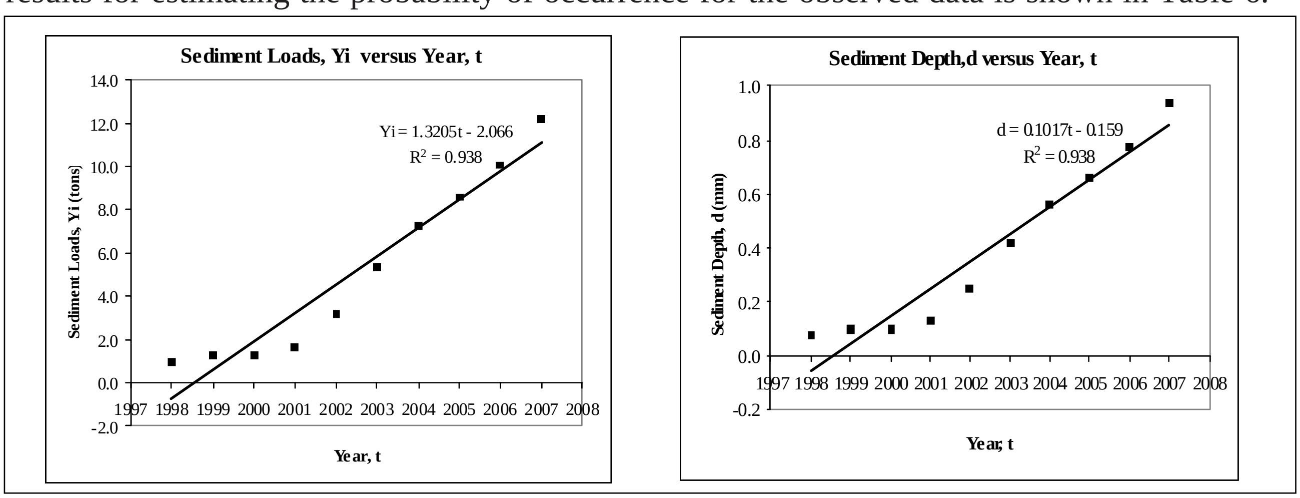

Figure 3. Linear regression equations for sediment loads and sediment depth.

Table 4. The forecasted sediment loads and sediment depth accumulated in pond.

No.		MUSLE Method		Trap Efficiency Method	
of Year	Year	Load, Yi	Depth, d	Load, Yi	Depth, d
Forecasted	Forecasted	(tons)	(mm)	(tons)	(mm)
1	2008	12.460	0.960	1.218	0.094
10	2017	24.344	1.875	12.176	0.938
20	2027	37.549	2.892	24.352	1.875
30	2037	50.754	3.909	36.528	2.813
40	2047	63.959	4.926	48.704	3.751
50	2057	77.164	5.943	60.880	4.688
60	2067	90.369	6.959	73.056	5.626
70	2077	103.574	7.976	85.232	6.564
80	2087	116.779	8.993	97.408	7.502
90	2097	129.984	10.010	109.584	8.439
100	2107	143.189	11.027	121.760	9.377

The simulation shows the maximum occurrence value for observed sediment loads was 0.0062 tons (16.51%), while the maximum occurrence value of observed sediment depth by was 0.0005 mm (17.53%). The most likely range for observed sediment loads obtained varies from 0.0031 to 0.0077 tons with percentage of occurrence of 11.93% to 15.47%. The most likely range for observed sediment depth are 0.0003 to 0.0006 mm which gives a percentage of occurrence of 12.83% to 15.24%.

Predicted Sediment Loads and Sediment Depth

The predicted sediment loads and sediment depth were calculated using the MUSLE and trap efficiency methods as explained before. As with the observed data, the predicted data also was run by MCS. Table 7 shows the input and variations value of output results for predicted sediment loads and sediment depth in the MCS by using the MUSLE method and trap efficiency method respectively.

The most likely values also would be observed from the simulation by taking the fourth higher values between the histograms or probability density curve. These likely values represent the most likely range for probability of sediment loads and sediment depth to occur within 100 years duration. These probability values are shown in the probability density curves in Figures 6 and 7. The summary of the results of estimating the probability of occurrence for the 100 years period data is shown in Table 8.

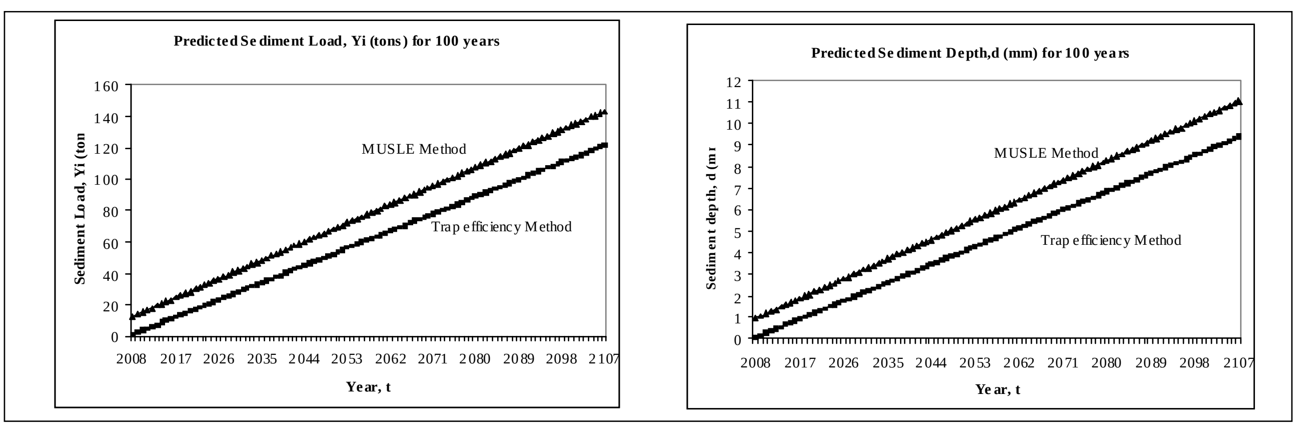

Figure 4. Predicted sediment loads and sediment depth for 100 years duration.

Table 5. Simulation outputs for observed sediment loads and sediment depths.

Note	Sediment Loads, Yi (tons)		Sediment Depth, d (mm)	
Actual Mean	0.006		0.0004	
Actual Standard Deviation	0.012		0.0009	
Number of Trials	500	20,000	500	20,000
Mean Value	0.00630	0.00604	0.00043	0.00041
Standard Deviation	0.01215	0.01203	0.00094	0.00090
Median Value	0.00623	0.00619	0.00044	0.00041
Standard Error	0.00054	0.00009	0.00004	0.00001
Skewness[a]	0.07	-0.03	0.01	0.01
Kurtosis[b]	2.92	3.03	2.99	2.99

[a] Skewness refers to the degree of asymmetry of a distribution. The normal distribution should be perfectly symmetric, with a skewness value of 0

[b] Kurtosis is the degree of peakedness of a distribution, relative to a normal distribution. Perfectly normally-distributed data will have kurtosis of 3.

The summary of MCS for predicted data showed the maximum probability of occurrence value for predicted sediment loads and depth by the MUSLE method were 77.753 tons (16.80%) and 7.524 mm (26.79%) respectively. The maximum probability of occurrence value for predicted sediment loads and depth by trap efficiency method were 61.056 tons (14.38%) and 6.181 mm (28.76%) respectively. The most likely range for predicted sediment loads varies from 68.139 to 82.514 tons (12.32% to 14.72%) and 52.009 to 66.696 tons (11.91% to 13.05%) for the MUSLE and trap efficiency methods respectively. The most likely range for predicted sediment depth was 6.738 to 7.955 mm (10.54% to 21.83%) and 5.444 to 6.583 mm (11.74% to 20.53%) for each method.

In other studies, the accumulation rate of sediment was found to average 18 mm per year (Buren et al., 1996) and range from 10 – 40 mm per year (Marsalek, 1995). Another study of accumulation of sediment during 18 months after a pond was constructed showed a 5 – 8 cm layer of sediments had accumulated near the inlet and a 1.5 cm layer near the outlet of the pond (Farm, 2002). The variation of sediment rate and depth was influenced by the sediment inflows into the detention pond from the corresponding watershed area.

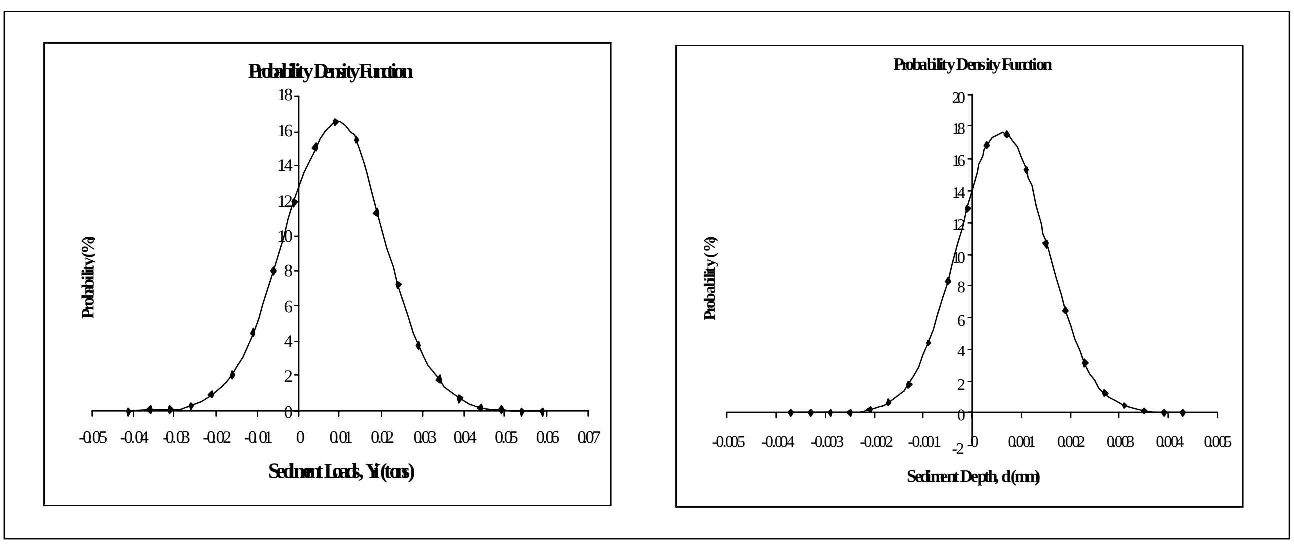

Figure 5. Probability density function of observed sediment loads and depth, 20,000 trials (Monte Carlo simulation).

Table 6. The output summary from the Monte Carlo simulation analysis with best normal distribution.

Note	Maximum Value	Maximum Percent*	Most Likely Range	Most Likely Percent**
Sediment Load, Yi (tons)	0.0062	16.51%	0.0031 – 0.0077	11.93 – 15.47%
Sediment Depth, d (mm)	0.0005	17.53%	0.0003 – 0.0006	12.83 – 15.24%
* Maximum Percent is the percent of maximum value of loads and depth obtained for the particular simulation				
** Most Likely Percent is the percent of most likely range of loads and depth obtained for the particular simulation				

CONCLUSION

Uncertainty analysis is one methods for predicting and forecasting of future values. MCS represents the simplest method to calculate the probability of occurrence of the sediment load and sediment depth accumulation in a detention pond. The simulation conducted here showed the maximum occurrence value for observed sediment loads was 0.0062 tons (16.51%). The maximum occurrence value of observed sediment depth by was 0.0005 mm (17.53%). The most likely range for observed sediment loads varied from 0.0031 to 0.0077 tons, with percentage of occurrence of 11.93% to 15.47%. The most likely range for observed sediment depths are 0.0003 to 0.0006 mm which are percentages of occurrence of 12.83% to 15.24%.

The maximum values for predicted sediment loads and depth by the MUSLE method were 77.753 tons (16.80%) and 7.524 mm (26.79%) respectively. The maximum values of predicted sediment loads and depth by the trap efficiency method were 61.056 tons (14.38%) and 6.181 mm (28.76%) respectively. The most likely range for sediment loads varies from 68.139 to 82.514 tons (12.32%-14.72%) and 52.009 to 66.696 tons (11.91%-13.05%) for each analysis. The most likely range for sediment depth was 6.738 to 7.955 mm (10.54%-21.83%) and 5.444 to 6.583 mm (11.74%-20.53%) for the MUSLE and trap efficiency methods respectively. The sediment depth value obtained from the forecasted analysis showed there are very small values of sediment accumulated and affected by the efficiency of the detention pond. This may be influenced by the

Table 7. Simulation output for predicted sediment loads and sediment depth.

Note	MUSLE Method				Trap efficiency Method			
	Sediment Loads, Yi (tons)		Sediment Depth, d (mm)		Sediment Loads, Yi (tons)		Sediment Depth, d (mm)	
Actual Mean	77.824		5.993		61.489		4.735	
Actual Standard Deviation	38.31		2.95		35.324		2.72	
Number of Trials	500	20,000	500	10,000	1,000	20,000	500	20,000
Mean Value	76.113	77.615	5.769	5.992	61.872	61.23	4.847	4.753
Standard Deviation	36.867	38.275	2.858	2.937	35.043	35.301	2.644	2.728
Median	75.731	77.753	5.609	5.979	63.049	61.056	5.022	4.763
Standard Error	1.647	0.271	0.128	0.029	1.108	0.25	0.118	0.019
Skewness[a]	0.10	-0.01	0.01	0.00	-0.05	0.02	0.03	-0.01
Kurtosis[b]	3.10	2.99	2.72	2.99	2.93	2.95	3.18	3.00
[a] Skewness refers to the degree of asymmetry of a distribution. The normal distribution should be perfectly symmetric, with a skewness value of 0								
[b] Kurtosis is the degree of peakedness of a distribution, relative to a normal distribution. Perfectly normally-distributed data will have kurtosis of 3.								

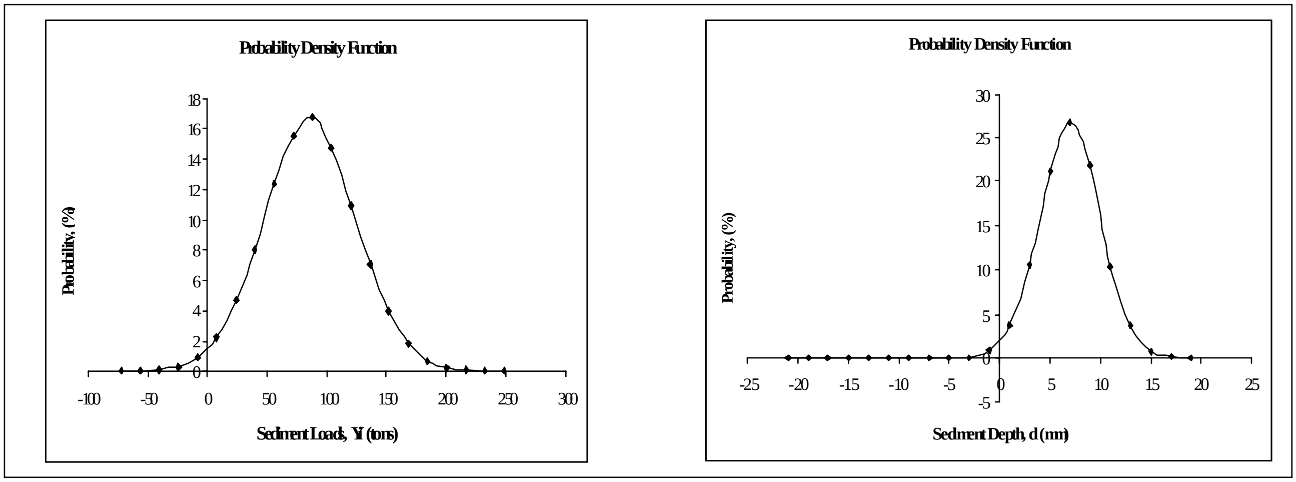

Figure 6. Probability density functions, (PDF) of sediment loads and sediment depth using MUSLE.

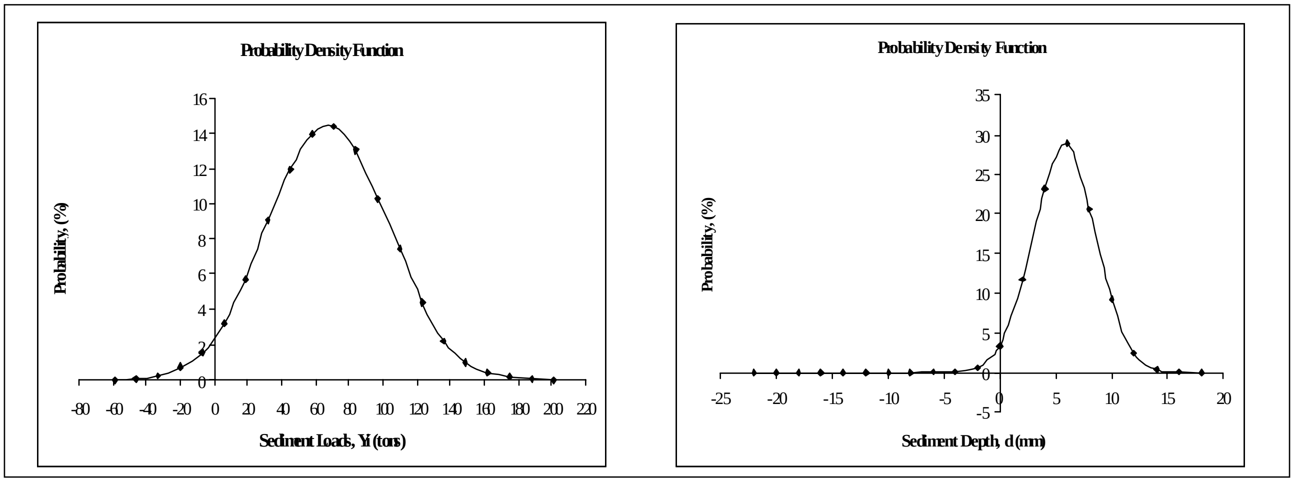

Figure 7. Probability density functions, (PDF) of sediment loads and sediment depth using Trap Efficiency Method.

Table 8. Summary of the probability density functions of predicted data.

Note	Maximum Value	Maximum Percent*	Most Likely Range	Most Likely Percent**
MUSLE Method				
Sediment Load, Yi (tons)	77.753	16.80%	68.139 – 82.514	12.32 – 14.72%
Sediment Depth, d (mm)	7.524	26.79%	6.738 – 7.955	10.54 – 21.83%
Trap Efficiency Method				
Sediment Load, Yi (tons)	61.056	14.38%	52.009 -66.696	11.91 – 13.05%
Sediment Depth, d (mm)	6.181	28.76%	5.444 – 6.583	11.74 – 20.53%
* Maximum Percent is the percent of maximum value of loads and depth obtained for the particular simulation				
** Most Likely Percent is the percent of most likely range of loads and depth obtained for the particular simulation				

wetland constructed before the inlet of the pond that reduced the quantity of the sediments flowing into pond. When the incoming sediment depths are measured daily and analyzed for longer periods, a better estimation of the accumulation sediment rate in the detention pond will be obtained.

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