Integrated Methodology of Design for Construction Site Sedimentation Basins

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Abstract: The performance of four sedimentation basins (SBs) at a Pennsylvania Department of Transportation I-99 highway construction site was evaluated based on their particle removal ability. Suspended solids data from the basins indicated poor particle removal, peaks in suspended solid concentration that correlated with rainfall peaks and possibility of sediment resuspension. The current Pennsylvania Department of Environmental Protection basis for basin design is the allocation of 28 m^3 (1,000 ft^3) of sediment storage zone and 140 m^3 (5,000 ft^3) of drainage zone per disturbed acre of the drainage basin. Overflow rate, which is a scientific basis for particle removal, is currently not considered in the design of basins. This paper presents a methodology for developing an integrated design for SBs, applying rainfall probability plots to determine an appropriate basin settling volume. The revised universal soil loss equation is used to identify sediment zone volume, and an overflow rate is determined to design basin surface area. The method presented is a comprehensive procedure for designing SBs with flexibility to choose the extent of particle removal and runoff capture, and to vary construction costs.

DOI: 10.1061/(ASCE)0733-9372(2008)134:8(619)

CE Database subject headings: Settling basins; Soil loss; Stormwater management; Runoff; Suspended solids; Integrated systems; Sedimentation.

Introduction

The Pennsylvania Department of Transportation (PennDOT 2002) is constructing US Route 220/I-99/SR 6220, which is part of a larger effort to extend I-99 North to I-80 at Bellefonte, Pa. Several sedimentation basins (SBs) have been constructed for highway construction purposes to collect the runoff from the site and remove suspended particles by retention. In order to evaluate the particle removal capacity of these SBs, four basins, SB11 (it was also part of a hydrologic study of the basin), SB14 (appeared constantly turbid), SB103 (received acid mine type constituents), and SB111 (in an area of intense construction activity), were selected for monitoring. Between September 2004 and August 2005, 10 field sampling trips were conducted, during which water samples were collected from the basin inlets and outlets. The SB samples were analyzed for total suspended solids (TSS), total iron, magnesium, manganese, aluminum, calcium, sulfate, and phosphate. The data showed peaks in concentrations of TSS and particulate contaminants including iron, aluminum, manganese, and phosphate that closely correlated to localized rainfall peaks. For certain samples, the concentration of TSS in the outlet was higher than the TSS concentration at the basin inlet, suggesting a possibility of sediment resuspension. In general, SBs attenuated high flows during wet weather events, but were not effective in capturing particulates. This shortcoming suggested that a different methodology or best-management practice for SB design needs to be developed to reduce particulate contaminants present in soil sediments from being released into the environment.

The design aspects that are integrated into the suggested design of SBs include:

1. Calculation of SB volume based on the percentage of storms that are required to be captured completely within a given duration;
2. Designing basin outflow rate and basin area based on overflow rate, which would directly translate into suspended solid removal; and
3. Calculating sediment delivery into the basin, the sludge zone volume, and the sediment dredging frequency that need to be maintained to control resuspension of settled solids.

Suspended Solids Removal by Basins

The National Pollution Discharge Elimination System (NPDES) permit for construction activities in Pennsylvania (PA) requires meeting the existing "PA Chapter 102, Erosion Control Rules and Regulations" and emphasizing pollution prevention through the use of best-management practices (BMPs). The program requires all earthmovers to develop, implement, and maintain erosion control measures and facilities that are detailed in an erosion and sedimentation (E&S) plan. Current practice is that specific effluent limits and sampling requirements are not required (Com-

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Note. Discussion open until January 1, 2009. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on February 8, 2007; approved on November 1, 2007. This paper is part of the ***Journal of Environmental Engineering***, Vol. 134, No. 8, August 1, 2008. ©ASCE, ISSN 0733-9372/2008/8-619–627/$25.00.

Table 1. Total Suspended Solids Concentration (mg/L) in Sedimentation Basin Samples[a]

Sample date	SB11 inlet-38	SB11 inlet-39	SB11 outlet	SB14 inlet-44	SB14 inlet-45	SB14 outlet	SB103 inlet	SB 103 outlet	SB111 inlet	SB111 outlet
September 22, 2004	23	16	40	NF	NF	325	NF	51	NF	20
October 5, 2004	25	18	44	NF	NF	77	NF	18	NF	19
October 20, 2004	12	12	10	NF	NF	98	NF	24	4	13
November 3, 2004	37	28	42	NF	NF	107	NF	33	NF	26
November 17, 2004	16	11	9	NF	NF	35	NF	17	NF	13
December 1, 2004	62	650	206	1,442	168	630	91	114	116	77
April 21, 2005	12	9	18	NF	NF	17	NF	8	NF	45
May 4, 2005	46	24	60	NF	NF	21	NF	27	NF	43
June 23, 2005	91	NF	75	NF	NF	48	NF	48	NF	NF
July 26, 2005	40	34	25	NF	NF	54	NF	40	NF	NF
Average	36	89	53	1,442	168	141	91	38	60	32
Maximum	91	650	206	1,442	168	630	91	114	116	77

Note: NF=no flow (samples were unavailable due to absence of flow in the inlets and outlets).

[a]Flow rate of runoff into and out of the sedimentation basin is not available.

monwealth of Pennsylvania 2006; PADEP 2004). TSS effluent limits for industrial site stormwater runoff are as follows: (1) instantaneous maximum 60–100 mg/L; (2) daily maximum 45–100 mg/L; (3) weekly average 45 mg/L; (4) monthly average 30 mg/L; and (5) annual average 50 mg/L. The above limits apply to industrial site stormwater runoff and not construction site runoff. At the present time there are no numeric effluent limits of construction site stormwater runoff (PADEP 2005), but since it is possible that effluent limits similar to the above may be applied to construction site stormwater runoff in the future, the TSS data presented in Table 1 may be compared to these limits.

A total suspended solids data summary from laboratory analysis of SB influent and effluent is shown in Table 1. TSS removal is significant only when the TSS concentration at the inlet is greater than 100 mg/L (1 kg/m^3), possibly due to the presence of large particles that settle out quickly. Furthermore, the average sedimentation basin effluent TSS concentration is greater than 50 mg/L (0.5 kg/m^3), which is the suggested average annual TSS effluent limit for industrial site stormwater runoff as shown in Table 1. For both SB11 and SB14, several peaks in TSS concentration can be observed where TSS exceeds 100 mg/L (1 kg/m^3) (instantaneous maximum). Examination of the TSS data summary in Table 1, and the variation in inlet and outlet TSS concentration for SB11 in Fig. 1, shows that the SBs have not been designed for particle removal. Hence, peaks in sediment concentration are not attenuated at high flow conditions and particle removal is not significant at other times. In addition, Fig. 2 shows there is an increase in contaminant concentration concomitant with a peak in the rainfall event. Table 1 shows several instances were the SB effluent exceeds TSS effluent limits for industrial site stormwater runoff. This may be of concern if future effluent limits similar to that for industrial site stormwater runoff are applied to construction sites. In this case, the present practice for the design of sedimentation basins will not provide desired particle removal. Furthermore, many particulate heavy metals are correlated with sediment suspended solids, and enhanced TSS removals in SBs will lead to reduced effluent metal loadings to the down-slope environment. Hence, it is necessary to develop a methodology for designing SBs that leads to removal of sediments from runoff and attenuates TSS peaks during heavy rainfall events.

Current Design Practices

The existing design criteria for SBs associated with construction sites for Pennsylvania (PADEP 2000) requires that a 28 m^3

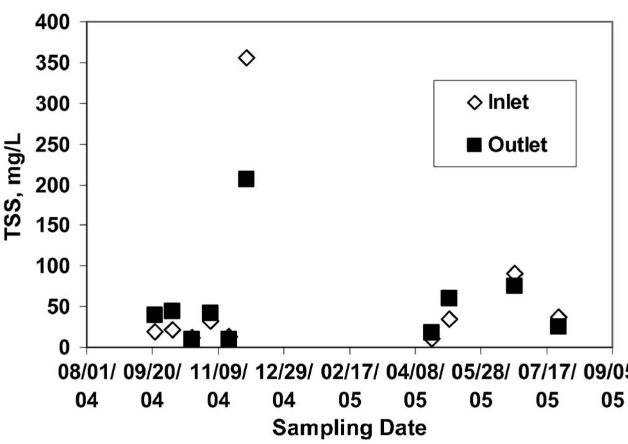

Fig. 1. Variation in average inlet and outlet concentration for SB11

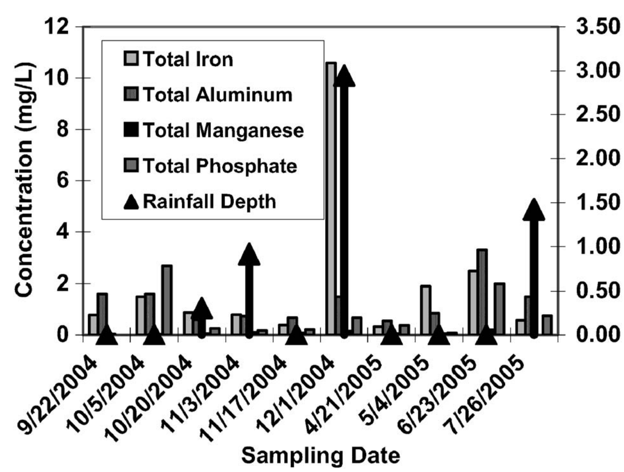

Fig. 2. Variation in particulate contaminants in SB11 outlet with rainfall

(1,000 ft^3) sediment storage zone per disturbed acre within the watershed and a drainage zone of 140 m^3 (5,000 ft^3) for each acre of associated tributary to the basin be provided. The SB design criteria according to U.S. Environmental Protection Agency (USEPA 1992) for SBs that serve an area with 10 or more disturbed acres at one time is the provision of about 100 m^3 (3,600 ft^3) of storage per acre drained. PADEP design criteria also suggests a drainage time of 2–7 days for SBs (PADEP 2000).

The site specific design for SBs at the I-99 construction site shows that the SBs have been designed according to existing PADEP design criteria cited above. Accordingly, overflow rate or particle removal was not considered in the basin design. Best-management practices for highway SBs suggest that 75–90% of total annual rainfall should be considered while managing runoff for water quality (PACD 1998). In addition, the use of the revised universal soil loss equation (RUSLE) for selecting alternative BMP configurations has been suggested (PACD 1998). However, there appears to be no current theoretical holistic procedure for arriving at highway construction sediment basin volume, sediment storage zone volume, sediment dredging frequency, and basin drainage time. Review of the literature and existing design criteria for SB design, suggests that an integrated and rational method for designing SBs is needed.

Steps for Developing SB Design

The following steps illustrate the method developed by this research leading to an integrated design and suggested best-management practice for SBs. As an example, each of the steps below is explained by application to the redesign of a sedimentation basin based on the drainage area of the I-99 basin labeled SB111. The basin design is developed for two different runoff capture conditions and a comparison between existing and developed designs is presented.

Rainfall Probability Plot and Settling Zone Volume

Precipitation frequency estimates up to an average reoccurrence interval (ARI) of 1,000 years can be obtained from the National Oceanic and Atmospheric Administration's National Weather Service Database (Bonnin et al. 2004). Precipitation frequency data for a 24-h storm up to a 100-year return period obtained from National Weather Service Database (Bonnin et al. 2004) are given in Table 2. The exceedence probability p can be calculated from the average reoccurrence interval also called the return period using the relation (Chow et al. 1988)

$$p = 1/\mathrm{ARI} \tag{1}$$

where p=exceedence probability (ratio, dimensionless); and ARI =average reoccurrence interval (or return period) in years.

In order to identify, the settling volume of the SB, a plot of nonexceedence probability (100% exceedence probability) and runoff volume is developed. Runoff volume V_R can be calculated using the relation

$$V_R = ar\,\mathrm{DA}\,\alpha \tag{2}$$

where V_R=runoff volume (ft^3 or m^3); r=precipitation depth (in. or cm); DA=drainage area (ft^2 or m^2); a=conversion factor (0.0833 ft/in. for U.S. units; 0.01 m/cm for SI units); and α=dimensionless runoff coefficient, the ratio of rainfall that contributes to runoff. Runoff volume can also be calculated by applying the Soil Conservation Service (SCS) method for calculating excess rainfall. Where direct runoff

Table 2. Rainfall Frequency Estimates for State College, Pa.

ARI years	24-h storm (cm)	Exceedence probability (%)	Nonexceedence probability (%)	Runoff volume SB111 (m^3)
2	6.7	50	50	1,416
5	8.4	20	80	1,758
10	9.7	10	90	2,047
25	11.7	4	96	2,458
50	13.3	2	98	2,795
100	15.0	1	99	3,164

$$P_e = (r - 0.2s)^2/(r + 0.8s) \tag{3}$$

where P_e=excess rainfall (in. or cm); s=dimensionless factor and can be calculated using the relation; and

$$s = (1{,}000/\mathrm{CN}) - 10 \tag{4}$$

where CN=curve number estimated based on land use pattern (dimensionless).

The CN is selected based on the land use and soil conservation practice at the construction site and is available from the Soil Conservation Service database (Chow et al. 1988; SCS 1972). Runoff volume can be calculated as a product of drainage area and excess rainfall. Once runoff volume is calculated, a graph is plotted with nonexceedence probability on a probability scale versus runoff volume on a logarithmic scale. This graph should yield a straight line, and based on desired storm capture requirement, a nonexceedence probability can be chosen. The runoff volume corresponding to the nonexceedence probability chosen gives the settling volume of the SB.

If the SBs will be eventually used for both stormwater management and runoff capture in addition to sediment removal, then it would likely be necessary to design sedimentation basins for 99% nonexceedence probability (based on 100-year rainfall frequency estimates) as it corresponds to capture of flood from a 100-year storm. This is necessary because current Pennsylvania Department of Environmental Protection (PADEP) regulations require that stormwater management basins should be able to capture the flood resulting from a 100-year storm (PADEP 2003; PACD 1998).

On the other hand, if the only purpose of the SB is to retain sediments and maintain water quality during infrastructure construction, then the policy for basin design can accept a lower nonexceedence probability such as 90% (capture of a 10-year storm), 80% (capture of a 5-year storm) or even a 50% (capture of a 2-year storm) depending on the duration of the construction project. Since storms with a large return period (100 years) are expected to occur less frequently during the life of the construction project, their contribution to water quality is less compared to storms with a small return period that occur more frequently during the life of the construction project. Hence, designing water quality SBs for lower nonexceedence probability may result in smaller basins that cost less to install while offering the necessary environmental sediment removal protection.

For application to the design of SB111, assuming a runoff ratio of 0.9, and using a drainage area of 24,120 m^2 (259,618 ft^2, 5.96 acres) (as obtained from elevation map of the drainage basin), the runoff volume V_R can be calculated from Eq. (2), as

$$V_R = 0.9 \times 24{,}120 \times r(\mathrm{m}^3) \tag{5}$$

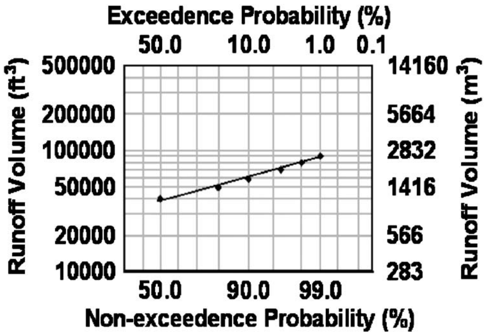

Fig. 3. Probability plot for SB111 developed from 100-year rainfall frequency data

The runoff coefficient α varies from 0.2 to 0.9 depending upon the type of land use. A runoff coefficient of 0.9 was chosen as a conservative estimate to avoid underestimating runoff into the basin (PADEP 2000). Table 2 shows the rainfall frequency estimates for State College, Pa., the location of the construction site (Bonnin et al. 2004). The corresponding values of runoff volume and nonexceedence probability are also shown in Table 2. Fig. 3 shows the probability plot developed from 100-year rainfall frequency estimates (Table 2). Once vehicular traffic uses the highway, sedimentation basins at this construction site will eventually be used for both runoff capture and sediment removal. Therefore, a basin settling volume corresponding to 99% nonexceedence probability was used for this design. The runoff volume corresponding to 99% storm capture is 3,080 m^3 (110,000 ft^3). Thus, the settling volume for SB111 for capturing runoff from a 100-year storm will be 3,080 m^3 (110,000 ft^3).

RUSLE2 for Calculating Sediment Zone Volume

RUSLE is a set of mathematical equations that estimates average annual soil loss and sediment yield resulting from interrill and rill erosion. It was developed by scientists from various fields including agricultural engineers, civil engineers, agronomists, soil scientists, geologists, hydrologists, geomorphologists, and soil conservationists of the Soil and Water Conservation Society in 1993. It was derived from the theory of erosion processes, using more than 10,000 plot years of data from natural rainfall plots and numerous rainfall-simulation plots (Renard et al. 1997). RUSLE retains the structure of its predecessor, the universal soil loss equation (Wischmeier and Smith 1978)

$$\mathrm{ASL} = RKLSCP \tag{6}$$

where ASL=average annual soil loss

$$\frac{\text{tons}}{\text{acre year}}\left(\frac{\text{tonnes}}{\text{m}^2\ \text{year}}\right)$$

R=rainfall/runoff erosivity

$$\frac{\text{foot}-\text{ton}f-\text{in.}}{\text{acre}-\text{h}-\text{year}}\left(\frac{\text{m}-\text{kN}-\text{cm}}{\text{m}^2-\text{h}-\text{year}}\right)$$

(1 ton$f$=1 short ton×gravity=907×9.81≈8.89 kN); K=soil erodability

$$\frac{\text{ton}-\text{acre}-\text{h}}{\text{acre}-\text{ft}-\text{ton}f-\text{in.}}\left(\frac{\text{ton}-\text{m}^2-\text{h}}{\text{m}^3-\text{kN}-\text{cm}}\right)$$

L=slope length

$$\frac{\text{ft}}{\text{ft}}\left(\frac{\text{m}}{\text{m}}\right)$$

S=hill slope steepness (dimensionless); C=cover management (dimensionless); P=support practice (dimensionless).

The RUSLE can be used to calculate soil loss from construction sites, mined land, and reclaimed lands in addition to agricultural lands. Some of the applications of RUSLE, with respect to construction sites, are (1) assessment of alternative hill slope configurations (convex, uniform, concave, and complex); (2) obtaining erosion-control or erosion-reduction credit for the surface rock fragment covers; and (3) analyses of the effects of straw mulch, random roughness, soil consolidation, sediment deposition, and changes through time due to mulch decomposition and deterioration of surface roughness due to rainfall (Toy et al. 1998). The sediment yield calculated from RUSLE can be used for identifying the sediment volume required for SB. Searching the literature reveals that RUSLE has not been applied to SB design in the past. RUSLE can be used to calculate sediment yield from SB drainage area and the sediment yield thus calculated can be used to set the sediment storage volume and the frequency of sediment removal for the basin.

The Windows-based computer version of RUSLE, namely RUSLE2, was used to calculate the sediment yield from the SB111 drainage area. The drainage area as shown on an elevation map was divided into five segments of varying slopes. The slope length and slope steepness of each segment were input into the RUSLE2 program. Table 3 gives the slope length and steepness of each segment.

RUSLE2 is used to calculate soil loss and sediment yield at the toe of the slope resulting from rill and interrill erosion. The RUSLE2 program calculates the soil yield at the toe of the drainage area by adding the soil loss from each segment and subtracting the local soil deposition, if any, to yield the final value. In addition to slope length and steepness, inputs including soil, vegetation, type of soil management, and climate data were also provided.

The climate data for Centre County, Pa., were imported from the climate database provided in the Natural Resources Conservation Service (NRCS 2004) website for use with RUSLE2. Similarly data files on soil types and soil management for Center County, Pa., was also imported into the program from the NRCS database. The soil type for the drainage basin was identified to be "LDF LAIDIG Extremely Stony Loam" from the Soil Survey for Centre County, Pa. (USDA-SCS 1981). As inputs for soil management, the input variable of "a single year special seed clover" was chosen for the segments of the drainage area where vegetation was used as a management practice. A construction site template defined within RUSLE2 was used as management type for the segments of drainage area where earth movement was prevalent due to construction.

Basin Volume—Results and Discussion

The soil yield and the soil loss calculated by RUSLE were 36 kg/m^2/year (160 ton/acre/year) and 72 kg/m^2/year (320 ton/acre/year), respectively. The value of soil yield at the toe of the slope is less than the annual average soil loss due to intermediate deposition of soil along the hill slope before reaching the toe. As the soil deposited along the hill slope can be further eroded during subsequent storm events or construction activity, the average of soil loss and soil yield values have been used as an estimate of soil delivered into the sedimentation basins. Thus, an

Table 3. Slope Length and Percentage Steepness of Sedimentation Basin No. 111

Segment number	Slope length (along slope) (m)	Slope length (horizontal length) (m)	Slope steepness (%)
1	12.2	11.6	35
2	12.2	12.2	5.0
3	15.2	14.9	20
4	15.2	15.2	4.0
5	48.8	45.7	43

average estimate of soil delivered into the sedimentation basin 111 from its drainage area is 54 kg/m^2/year (240 ton/acre/year). Applying this value as the average soil yield from the drainage basin that enters the SB, the sediment volume that is required to be provided and the frequency of the sediment dredging cycle can be arrived at, as shown below:

- Drainage area for SB111=24,120 m^2 (259,618 ft^2, 5.96 Ac);
- Sediment delivery t/AC/year=54 kg/m^2/year (240 ton/Ac/year);
- Assuming specific gravity of sediment=2.65 (Davison et al. 2000); and
- Sediment storage volume=240×907.2 (kg/Ac/year) $\times 5.96$ [Ac]/2,650 (kg/m^3)$\cong$481(m^3/year)[17,000 (ft^3/year)]

If a sediment dredging frequency of n years is preferred for maintenance purposes, then the sediment volume can be calculated as $(n \times 481)m^3$. Thus, considering a sediment dredging frequency of two years, the sediment volume for SB111 would be $2 \times 481 \cong 962$ m^3 (34,000 ft^3). The present sediment volume of SB111 is 431 m^3 (15,228 ft^3), which would require sediment dredging every 11 months. It must be noted that the sediment in SB111 at the I-99 construction site has not been dredged since its construction in April 2004. According to the soil yield from RUSLE, the volume of sediment in the basin in June 2006 should be about 1,047 m^3 (37,000 ft^3). A field visit was made in June 2006 and the sediment depth in SB111 was found to be 3 ft (0.9 m), which is 1.5 ft (0.5 m) above the sediment storage zone. The sediment volume corresponds to $\cong$934 m^3 (33,000 ft^3). Though lesser than the RUSLE predicted soil volume, this appears to be a reasonable value as some soil may have been lost due to sediment resuspension and release in the outlet.

Calculating Basin Outflow Rate and Area Based on Basin Overflow Rate

The required design overflow rate for particle removals can be calculated by determining the size of the particle that has to be removed completely in the basin. Either a nominal particle size can be chosen for removal or the particle size distribution data (PSD) of the runoff from the site can be analyzed to identify the particle size for removal. PSD of a stormwater runoff sample from construction sites in the region may also be analyzed to identify the nominal particle size for removal if that is the best data available. As sedimentation basins are constructed before construction activities begin at the site, samples obtained from the site to study PSD before construction will be different from that during construction activity; hence, the suggestion of comparing the particle size distribution at other construction sites in the region is being suggested herein, for the identification of nominal particle size to be removed in the basin. It appears that there is a need to classify soil particle-size distribution in various geographic locations, so that a representative PSD is available for different locations and this could be one of the areas of future research. If PSD data are available then the procedure explained below can be used with more confidence for SB design.

Table 4. Particle Size Distribution Data for Sedimentation Basin No. 111 Sediment Samples

Particle size range (particle diameter, μm)	Mass percentage (less than diameter)
45	57
33	51
27	49
24	46
21	46
15	42
13	39
9.1	34
6.5	31
4.7	27
3.3	24
2.3	17
1.4	12
0.8	7

The settling velocity for the nominal particle size can be calculated from Stokes's law (Gregory et al. 1999). Design overflow rate for the basin is given by V/A, where V=volume of the basin and A=surface area. Overflow rate has units of velocity and can be associated with the velocity of the smallest particle that is removed completely in the basin. Therefore, the design overflow rate of the basin is set equal to the settling velocity of that particle (Gregory et al. 1999).

The PSD of SB111 sediment samples were analyzed using hydrometer testing. The data obtained from hydrometer analysis (ASTM D 422) of the sediment sample are shown in Table 4. If we assume that the PSD of inflow to the basin is similar to that of basin sediments, then from the sediment PSD data in Table 4, we see that removing particles with a diameter of 2 μm would constitute to roughly 85% particle removal by weight. For example, if the influent TSS concentration was 100 mg/L, then setting the overflow rate corresponding to 2 μm particle removal will result in an effluent TSS concentration of 15 mg/L. Thus, to achieve 85% particle removal, the design overflow rate for SB111 would be set to 0.3 m/day (7.48 gal/ft^2/day, 1.0 feet per day), which is the settling velocity corresponding to 2 μm particle as calculated from Stokes law at 25°C assuming a particle density of 2,650 kg/m^3 (Gregory et al. 1999; Davison and Springman 2000). The PSD data used herein were obtained from a basin sediment sample. Realistically, however, the PSD of influent to the basin should be used; however, due to the absence of flow in the inlets during several field visits, the PSD data from collected sediments have been used.

Sedimentation Basin Design and Configuration

To ensure structural stability, a typical SB is currently constructed with tapering side walls. Due to its shape, the area of the SB varies along the depth of the basin. The outflow device used to release stormwater from the basin is usually a perforated riser (Fig. 4). While designing the sedimentation basin, the area and volume of the basin at different depths of the basin have to be calculated. The outflow rate through the outflow structure also varies along the depth of the basin. It can be seen from Fig. 4

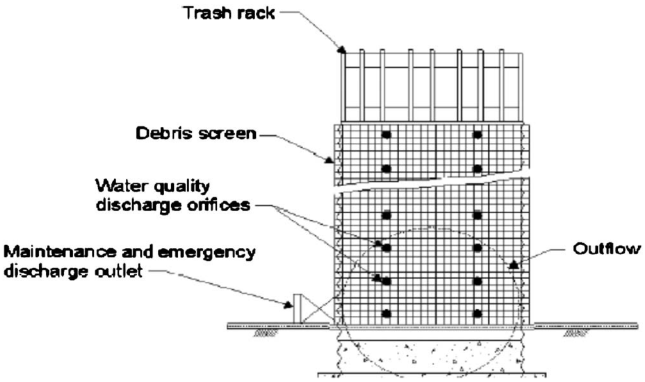

Fig. 4. Multiple Orifice Outlet Riser [*California Stormwater BMP Handbook* (CASQA 2003)]

that the riser has a number of discharge openings along its length. As the water level in the pond increases, the discharge flow through the riser also increases since it intercepts additional exit holes.

In order to set a minimum design overflow rate, the outflow through the riser must be designed such that the outflow rate at any depth divided by the corresponding area yields a minimum overflow rate. That is

$$Q_d/A_d = \mathrm{OR}_d \text{ m/day(ft/day)} \quad (7)$$

where (Q_d)=outflow rate as a function of depth d [$\mathrm{m}^3/\mathrm{day}(\mathrm{ft}^3/\mathrm{day})$]; A_d=area at depth d [$\mathrm{m}^2(\mathrm{ft}^2)$]; and OR_d=overflow rate at depth d [m/day (ft/day)].

There is no outflow from the basin in the sediment zone as this volume is reserved for sediment storage. Drainage of water from the basin begins at the settling zone.

Sedimentation Basin Design Parameters

The design parameters for SB111 were developed by applying the method discussed above. Two alternative designs were developed and compared with the existing design, namely, (1) for a 100-year design storm (99% storm capture in any given year), 2 μm particle removal and 2-year dredging frequency and (2) for a 5-year design storm (80% storm capture), 2 μm particle removal and 2-year dredging frequency. Fig. 5 shows the sequence of steps to be followed for designing the sedimentation basin. As the first step to developing sedimentation basin design, assume an area A_0 at the base of the basin at depth $d=0$. Assume a side slope and compute area at every 0.5 or 1 ft increase in depth. The area can be computed at smaller intervals of depth based on the level of accuracy needed. Calculate the average area at each depth increment. As an example, average area at depth $d=d1$ will be $(A_{d1}+A_0)/2$ and average volume at depth $d=d1$ will be $(A_{d1}+A_0)(d1/2)$. Assume sediment depth d_s. Calculate the cumulative volume at depth d_s, by summing the average volume for depth intervals between d_0 to d_s.This volume should correspond to the sediment volume required for the basin. If not, adjust base area of the basin or the sediment depth d_s until the cumulative volume matches the sediment volume. Similarly, the cumulative volume for the depth intervals from d_s to d_f should match the settling volume required for the basin. If not, adjust base area, d_s or d_f to obtain a cumulative volume that matches settling volume. Once the appropriate settling depth, sediment depth and area of the basin have been arrived at by the method of trial and error mentioned above, calculate the outflow rate for each depth interval in the settling zone by using the formula shown in Fig. 5. It must be noted that overflow rate is a constant and is chosen based on the size of particle to be removed in the basin. The outflow rate thus calculated should be used to design the riser. If outflow rate is too high or too low, such that it cannot be met by riser design, then the overflow rate or basin area must be varied to obtain reasonable outflow rates.

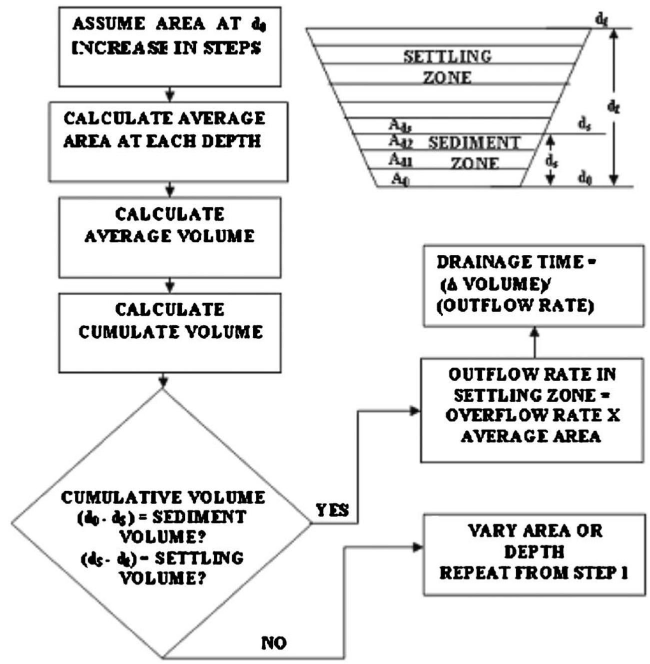

Fig. 5. Flow diagram of steps to be followed for designing sedimentation basins

Tables 5 and 6 show a design summary of the two design scenarios considered. In Tables 5 and 6, the first column is the depth of the basin. The depth, length, and breadth of the basin can be varied accordingly to attain the design sediment storage volume and settling zone volume. The outflow rate is the product of average area and design overflow rate, and the drainage time is obtained by dividing the average incremental basin volume by outflow rate. From Table 5 it can be seen that for the control of 99% of storms in a year (capture of runoff from a 100-year storm), for the removal of particles with a diameter of 2 μm and above and for a dredging frequency of two years, a basin 2.1 m (7 ft) in depth, having an area of approximately 2,700 m^2 (~29,000 ft^2) at the surface and having a drainage time of five days, is sufficient applying the integrated design method. Similarly, for the capture of 80% storms in a year, for the removal of particles with a diameter of 2 μm and above and for a dredging frequency of two years a basin 1.8 m (6 ft) in depth, having an area of approximately 2,000 m^2 (~22,000 ft^2) area at the surface and having a drainage time of four days is sufficient (Table 6) applying the integrated design method.

The existing design of SB11 is summarized in Table 7 and a comparison of the existing and developed design parameters is shown in Table 8. Comparing the existing design of SB111 with the design parameters developed using the integrated method, shows that this methodology helps to design sedimentation basin according to requirements and offers more choices in terms of basin performance and cost. From Table 8 it can be seen that if

Table 5. Design Summary of Sedimentation Basin No. 111 (100-Year Storm Capture, 2 μ-Particle Removal, and 2-Year Sediment Dredging Frequency)[a,b]

Depth from bottom (m)	Length (m)	Breadth (m)	Average area (m^2)	Cumulative basin volume (m^3)	Outflow rate (m^3/day)	Drainage time (day)
0.0	49	24				
0.2	50	26	1,234	188		
0.3	51	27	1,327	390		
0.5	52	28	1,422	607		
0.6	54	29	1,520	839		
0.7	54	30	1,600	985	488	5
0.8	55	30	1,651	1,086	504	4.7
0.9	56	32	1,725	1,349	526	4.5
1.1	57	33	1,832	1,628	558	4
1.2	59	34	1,942	1,924	592	3.5
1.4	60	35	2,055	2,237	626	3
1.5	61	37	2,171	2,568	662	2.5
1.7	62	38	2,290	2,917	698	2
1.8	63	39	2,412	3,285	735	1.5
2.0	65	40	2,537	3,671	773	1
2.1	66	41	2,664	4,077	812	0.5

[a]Outflow begins at the settling zone.

[b]Overflow rate was maintained constant at 0.3 m/day (7.48 gal/ft^2/day) at all depths in the settling zone.

both runoff capture from a 100-year storm as well as effective particle removal have to be achieved in the same basin, then a basin with large volume and surface area is required. On the contrary, if the decision policy is that runoff capture can be reduced for instance from 99% storm capture (100-year storm) to 80% storm capture (5-year storm), then basin volume and area required can be reduced significantly and would result in cost savings in terms of reduced basin volume requirements and reduced excavation costs during basin construction. It must be noted that the trade-off for surface area reduction is at the cost of drainage time, i.e., decreasing the surface area would also require an increase in basin depth, and would result in an increase in drainage time.

Table 6. Design Summary of Sedimentation Basin No. 111 (5-Year Storm Capture, 2 μ-Particle Removal, and 2-Year Sediment Dredging Frequency)[a]

Depth from bottom (m)	Length (m)	Breadth (m)	Average area (m^2)	Cumulative basin volume (m^3)	Outflow rate (m^3/day)	Drainage time (day)
0.0	43	21				
0.2	44	23	950	145		
0.3	45	24	1,031	302		
0.5	46	25	1,115	472		
0.6	48	26	1,202	655		
0.9	49	28	1,320	977	402	4
0.9	50	29	1,413	1,063	431	3.2
1.1	51	30	1,481	1,289	451	3
1.2	52	31	1,580	1,530	482	2.5
1.4	54	32	1,681	1,786	513	2
1.5	55	34	1,786	2,058	545	1.5
1.7	56	35	1,894	2,347	577	1
1.8	57	36	2,005	2,653	611	0.5

[a]Outflow begins at the settling zone.

[b]Overflow rate was maintained constant at 0.3 m/day (7.48 gal/ft^2/day) at all depths in the settling zone.

Table 7. Summary of Existing Sedimentation Basin No. 111 Design[a]

Depth from bottom (m)	Average area (m^2)	Cumulative basin volume (m^3)	Outflow rate (m^3/day)	Overflow rate (m/day)	Drainage time (day)
0.3	905	276			
0.5	1,019	431			
0.6	1,098	555	49	0.04	4.92
0.6	794	587	73	0.09	2.39
0.9	1,137	933	318	0.28	1.96
1.2	1,260	1,317	612	0.48	0.87
1.4	1,368	1,609	1,957	1.43	0.24
1.5	1,433	1,740	9,885	6.89	0.10
1.8	1,520	2,203	18,376	12.1	0.08
2.1	1,656	2,708	18,376	11.1	0.06
2.4	1,779	3,251	18,376	10.3	0.03

[a]Erosion and pollution control narrative (PennDOT 2002).

Increase in basin area would reduce basin depth and basin drainage time. The logical effect of reducing basin drainage time is a likely reduction in algae growth and mosquito breeding. It should be noted that a typical mosquito life cycle varies from 7 to 18 days, and maintaining pond detention time under seven days will help destroy the mosquito life cycle helping in controlling mosquito breeding in the basins (NCID 2004; WCDH 2006; Cornell 2002; AMCA 2006; UFL 1995).

In the existing SB111 design, the outflow rate increases as water level in the basin increases. This means that as the water level in the basin increases, the size of the particle removed increases. Thus, when the basin is almost full during a storm event, the basin particle removal is reduced and a greater amount of suspended solids are released in the basin outlet. Hence, peaks in TSS and particulate pollutants are not attenuated as confirmed by the collected data. The alternative design developed by the "integrated methodology" provides for a constant overflow rate, and at all depths the minimum particle size that can be removed in the basin remains the same. Consequently, significant attenuation of particulate peaks can also be expected when designing SBs using the proposed integrated method. Furthermore, the "integrated design" methodology allows for sedimentation basin designs based on decision variables of storm capture, particle removal, and sediment dredging frequency requirements.

Summary and Conclusions

Evaluation of the performance of sedimentation basins at the I-99 construction site shows that the basins are not been designed for particle removal or suspended solids peak attenuation. The frequency of sediment dredging for the basins is currently not a factor in design, but rather is performed when deemed necessary by on-site inspectors. In addition, sediment resuspension during wet weather events are apparent from collected TSS data. The basin design and performance showed that the basins have been designed for runoff flow capture rather than particle removal. A

Table 8. Comparison of Existing and Developed Design Parameters

Design parameter	Existing design	99% storm capture (2 μ-particle removal/ 2-year dredging frequency)	80% storm capture (2 μ-particle removal/ 2-year dredging frequency)
Basin volume	3,300 m^3	4,100 m^3	2,700 m^3
Basin depth	2.4 m	2.1 m	1.8 m
Area at surface	1,800 m^2	2,700 m^2	2,000 m^2
Particle removal	0.8–12.5 μ	2 μ	2 μ
Drainage time	5.0 days	5.0 days	4 days
Sediment volume	600 m^3	1,000 m^3	1000 m^3

review of the existing design practices for SBs revealed the need for an integrated system for the design of SBs.

The integrated design methodology discussed in this paper incorporates the application of rainfall probability plots to determine basin settling volume, RUSLE2 to identify sediment zone volume and sediment dredging frequency, and overflow rate to determine minimum particle size that can be removed in the basin and required basin area. The conclusions reached by comparing the existing design of SB111 and design developed for SB111 based on the proposed methodology are as follows:

1. The volume of the sedimentation basin can be a design variable depending upon storm capture requirements. When the basin is designed to capture storms that have short return periods, the basin volume and the associated construction costs can be considerably reduced.
2. A desired percentage of particle removal can be achieved by designing the pond with an overflow rate equal to the settling velocity of the particle to be removed. Depending upon the volume of the basin, maintaining the design overflow rate may lead to an increase in basin surface area compared to existing design practice.
3. Improved particle removal and suspended solids peak attenuation during high flow events can be achieved by maintaining a constant overflow rate at all depths of the pond.
4. Pond drainage time can be a design variable depending upon stormwater capture requirements, basin area, and minimum particle size removal requirement. In addition, a reduced drainage time can be instrumental in controlling mosquito breeding.
5. By applying RUSLE2 the average annual sediment delivery to the SB can be better predicted. Thus, for a given sediment volume the sediment dredging frequency in years can be calculated. This would give an estimate of how often a field inspection should be conducted to inspect pond sediment level and dredge sediments if necessary.

In conclusion, the integrated design methodology proposed herein for sedimentation pond design helps to address both runoff capture and particle removal requirements. It yields a design that helps in suspended solids peak attenuation during high flow events. It shows that basin drainage time can be reduced if necessary and issues of algae formation and mosquito breeding can be controlled. Further it presents a method to arrive at sediment storage volume, settling zone volume, and sediment dredging frequency specific to the construction site, which would help in controlling sediment resuspension. It can thus be said that the integrated design methodology offers more choices in terms of performance and cost and will be a significant advance to the existing methodology of designing sedimentation basins.

Notation

The following symbols are used in this paper:

A_d = area at depth d (m^2);
ARI = average reoccurrence interval (or return period) in years;
a = conversion factor (0.01 cm/m);
C = cover management (dimensionless);
CN = curve number estimated based on land use pattern (dimensionless);
DA = drainage area (m^2);
d_s = depth of settling zone (m);
d_f = depth of settling zone + depth of sediment zone (m);
K = soil erodability (ton$-$m$^2-$h/m$^3-$kN$-$cm);
L = slope Length (m/m);
OR_d = overflow rate at depth d (m/day);
P = support practice (dimensionless);
P_e = excess rainfall (cm);
p = exceedence probability (ratio, dimensionless);
Q_d = outflow rate as a function of depth d (m^3/day);
R = rainfall/runoff erosivity (m$-$kN$-$cm/m$^2-$h$-$year);
r = precipitation depth (cm);
S = hill slope steepness (dimensionless);
s = factor for curve number (dimensionless);
V_R = runoff volume (m^3); and
α = ratio of rainfall that contributes to runoff (dimensionless).

Acknowledgments

This work was sponsored by the Pennsylvania Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration. Site visit, field survey, and collection of water samples from the sedimentation basins were supported by GAI Consultants Inc.

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