Article 57

Technical Note #83 from Watershed Protection Techniques. 2(3): 429-433

The Limits of Settling

Sediment basins and traps face an imposing performance challenge in removing sediment from construction site runoff: massive incoming suspended sediment concentrations (Table 1). Field and modeling research indicate that average total suspended solid (TSS) concentrations from construction sites are about 4,500 mg/l (with some storms as high 17,500 mg/l). If a basin is capable of achieving an impressive removal rate of 90%, the basin would still discharge sediment at a concentration of 450 mg/l. This is noticeably muddy to any downstream observer. If a basin's removal rate is increased to 95%, the discharged TSS concentration is still 225 mg/l—again a highly turbid discharge by most standards. It takes a herculean removal effort—99% or more—to produce a TSS level (45 mg/l) that in any way resembles a clear water discharge. Is it realistic, then, to expect sediment basins to meet such an imposing performance challenge? This article reviews some recent field and modeling studies to examine how much removal can practically be expected from sediment basins.

Field Monitoring

Surprisingly few sediment basins and traps have been tested in the field. Of the limited number of performance monitoring studies that have been conducted, three of the most informative are Horner's (1990) study of three highway sediment basins in Washington state, Jarrett's (1996) Pennsylvania test basin study, and Schueler and Lugbill's (1990) study of five basins and traps in the suburban Maryland piedmont. These studies (entries 1 - 9 in Table 1) clearly suggest that basin removal rates are highly variable. A quick glance shows that three of the nine basins or traps were found to remove sediment at a rate above 94%, five basins were in the 55 to 85% range, and one trap removed less than 20% of incoming sediments (due to internal erosion at inlets).

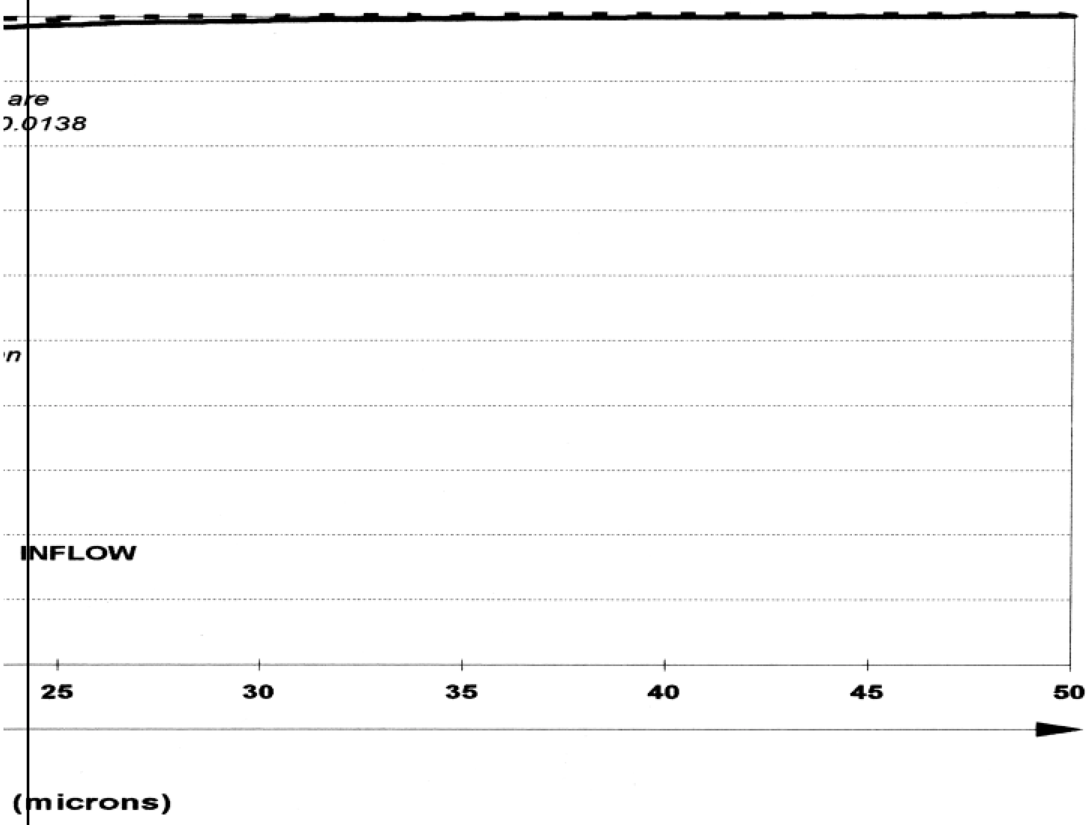
Table 1: The Performance of Sediment Basins and Traps
A Summary of Field, Laboratory and Modeling Results

Research study or site	TSS (mg/l) Mean inflow	Mean outflow	Mean % Reduction*
1. SR-204 [1]	3,502	154	98.6%
2. Seattle [1]	17,500	626	86.7%
3. Mercer Island [1]	1,087	63	75.1%
4. RT1 [2]	359	224	18.0%
5. RT2 [2]	4,623	127	99.8%
6. SB1 [2]	625	322	54.7%
7. SB2 [2]	415	91	80.3%
8. SB4 [2]	2,670	876	66.8%
9. Pennsylvania Test Basin [3]	9,700	800	94.2%
10. Georgia Model [4]	1,500 - 4,500	200 - 1,000	42 - 87%
11. Maryland Model [5]	1,000 - 5,000	200 - 1,200	68 - 99.5%
12. Uncontrolled construction site runoff (MD) [6]	4,200	—-	—
Means	4,498	365	75%

Sources:
[1] *Horner, Guerdy, and Kortenhof, 1990*
[2] *Schueler and Lugbill, 1990*
[3] *Jarrett, 1996*
[4] *Sturm and Kirby, 1991*
[5] *Barfield and Clar, 1985*
[6] *York and Herb, 1978*
* Note: Based on mean of individual storm removals.

Table 2: Computer Model Estimates of Removal Efficiencies for Sediment Basins (based on the 10-year, 24-hour Storm Event)

Modeling Study	Geography and Soil Type	Removal Efficiency
Sturm and Kirby, 1991	Sandy loam	82 - 87%
Georgia piedmont	Silty loam	70 - 77%
	Clay loam	54 - 42%
Barfield and Clar, 1985	Silt loam	68 - 97%
Maryland coastal plain	Clay loam	76 - 96%
	Sandy loam	94 - 99.5%
	Silt loam	68 - 97%
	Clay loam	76 - 96%



The particle size distribution becomes more fine-grained of sediment as it moves from inflow to outflow. Also, note that over 50% of all incoming sediments are less than ten microns in size at this construction site in the Maryland piedmont, implying that a very small design particle should be chosen for design.

Figure 1: Particle Size Distribution in Sediment Basin/Trap Inflow and Outflow (Schueler and Lugbill, 1990)

It is tempting to attribute removal rate variability to site and basin design differences. However, the removal rates for the basins and traps in the Schueler/Lugbill study varied significantly despite similar soil types, eroded particle soil size, and basin design criteria. A clear implication of the performance monitoring studies is that removal efficiencies are highly variable and that the current design of most basins is not capable of accomplishing the imposing challenge of 95 to 99% removal.

Modeling Studies

Sediment basins and traps at active construction sites are notoriously difficult to sample. Runoff events are inherently unpredictable and construction site activity can interfere with data collection. Some researchers avoid these difficulties by using computer models to predict removal efficiencies. Some prominent examples include the work of Barfield and Clar (1985) and Sturm and Kirby (1991). In each case, the performance of sediment basins was assessed for a very large storm event (10-year, 24-hour storm) and for a series of parent soil types. The predicted removal efficiencies are summarized in Table 2. In general, both model studies suggest that sediment basins can reliably achieve a much higher performance level than reported in the field. What accounts for the discrepancy between model predictions and field results?

Settling Theory Versus the Real World

Models and computer simulations used to estimate removal efficiencies use algorithms that simulate a behavior referred to as Type 1 settling. Three basic principles of Type I settling are (1) that the flow within the basin is quiescent; (2) that settling is governed by the particle size distribution of the incoming sediment (Stahre and Urbonas, 1990); and (3) that removal depends upon adequate detention time. “Real world” sediment basin design criteria require some practical and simplifying shortcuts. Most notably, a design particle is used to represent the spectrum of incoming sediment particle sizes.

Overall, the Type 1 settling theory is a good approximation of the complex settling process. The theory provides modelers with important insights into the mechanics of settling and allows researchers to examine and compare the relative merits of different basin designs while avoiding the vagrancies of field conditions.

The disconnect between models and reality occurs `when we forget that the theory cannot capture the full complexity of flow, adequately reflect particle size distributions observed in the field, nor anticipate the sporadic, turbulent nature of runoff events.

Complex Flow Patterns

Type 1 settling theory assumes quiescent flow conditions. Between runoff events, any water within sediment basins is assumed to be static and calm. During runoff events, however, basins may experience multilayered flow, turbulence, eddies, circulation currents, dead spaces and diffusion at outlets and inlets. These factors lessen the removal capability of the basin, particularly with respect to the very small particles (i.e., silts and clays) that often dominate construction site runoff.

The Design Particle: Smaller Than You Think

The design particle is a convenient representation of the entire range of incoming sediment particles. Sediment particle sizes range from big, bulky cobbles to microscopic fine clays (Table 3). The design particle used for sediment basin design is generally based on a larger particle, such as sand. The particle size distribution of incoming sediment to basins and traps, however, is typically skewed toward finer-sized particles (Figure 1) and is usually much finer than that of the parent soil. This shift toward finer-sized particles occurs because less energy is usually required to detach, entrain, and transport smaller particles in the overland flow from construction sites, in comparison to larger particles.

Finer-sized particles tend to behave as non-settleable solids. The electrostatic forces generated by their extremely small size tends to impede settling. It is very difficult to effectively remove most particles less than 10 microns in size (i.e., silts and clays) by sedimentation alone. Many of the smaller particles that enter sediment basins are eventually discharged from the same basin. In fact, the particle size distribution of discharge from basins and traps is typically dominated by fine-silts and clays (Figure 1).

Detention Time

Detention time is the amount of time that runoff remains in the basin to allow sediment to settle out. For a sediment particle to settle out, it must reach the bottom of the sediment basin before the water is discharged. The speed of the sediment particle as it falls to the basin bottom is the particle’s *settling velocity* and different sized particles settle out at different rates. Larger grained particles tend to settle out relatively swiftly. On the other hand, finer-sized particles have slower settling velocities and tend to remain suspended in the basin.

The settling velocity of the design particle is a key component of basin design. In an ideal situation, discharge from the basin would not begin until the design particle had settled out. Particles with settling velocities greater than the design velocity will be completely removed. Particles with slower settling velocities will be removed in the following ratio:

$$\frac{\text{actual settling velocity}}{\text{design settling velocity}}$$

Theory implies that longer detention will provide greater removal efficiencies. However, field and laboratory data have shown that most settling occurs within the first few hours and that little additional settling is gained by increasing the detention time. As much as 60% of the total removal is accomplished within the first six hours (Schueler and Lugbill, 1990) and additional increments of sediment removal are more difficult to obtain after the rapid initial settling.

Bringing It Together

What can be done to make field performance more closely match theoretical performance criteria? Based on our comparison of model studies and field monitoring results, the key is to re-examine sediment basin design theory and application by focusing on increased removal of smaller particles. Some steps toward this goal include the following:

Select Smaller Design Particles

Most basin designs begin with a design particle. Unfortunately, the design particle is usually more representative of the parent soil rather than the basin inflow. To obtain a more accurate design particle, field monitoring data or modeling studies can be used to obtain the particle size distributions. Selecting smaller design particles, more in line with silt and clay dominated runoff, should yield a more realistic settling velocity.

Provide More Storage

The connection between large storms and basin volume is very straightforward: the larger the basin, the more runoff that can be detained and the longer the detention time. However, as discussed in article 58, during larger storms, a significant portion of the runoff is being displaced from basins or is discharged prematurely because many basins are undersized. In such cases, the runoff from larger storms can be accommodated with extra storage. The extra storage should be of sufficient volume to ensure a minimum of two to six hours of detention during larger storms.

Extra storage will also improve basin performance during small, frequent storms. Detention time is really the issue during these smaller storm events. Because these storms occur more frequently, it is more likely that runoff from these events may be discharged prematurely, before settling has been completed. Extra storage allows runoff from frequent storm events to be detained instead of being pushed out by the influx of additional runoff.

Decrease Incoming Sediment Loads

The best way to decrease the amount of sediment leaving basins and traps is to reduce the amount of sediment entering them. This commonsense approach to sediment control has been echoed by many erosion and sediment control experts across the country (Brown and Caraco, 1996).

Summary

It is evident that while models are very useful in describing the fate of coarse-grained sediment particles under ideal settling conditions, they have a very limited ability to simulate the very complex

Table 3: Sediment Particle Sizes According to the U.S. Department of Agriculture

Sediment Particle Size Class	Particle Size (mm)	(microns)
Cobbles and boulders	> 10	>10,000
Gravel	2 - 10	2,000 - 10,000
Very coarse sand	1 - 2	1,000 - 2,000
Coarse sand	.5 - 1.0	500 - 1,000
Medium sand	0.25 - 0.50	250 - 500
Fine sand	0.10 - 0.25	100 - 250
Very fine sand	0.05 - 0.10	50 - 100
Silt	0.002 - 0.05	2 - 50
Clay	< 0.002	<2

settling dynamics associated with fine-grained and colloidial particles. Consequently, the high sediment removal rates for basins computed by such models need to be taken with a grain of salt. It does seem that the basic design of sediment basins and traps can be improved and made more reliable, but there are limits to settling. It is safe to assume that a 80 to 90% removal rate is probably the best that can be achieved under field conditions. Likewise, we should acknowledge that most sediment basins cannot reliably meet a "clear water" discharge concentration.

—WEB

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