Physical and Chemical Properties of Runoff Effluent from Beef Feedlots in Iowa

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Abstract

Beef feedlot runoff is a potential environmental contaminant. As such, it should be managed properly to preserve water quality. Primary treatment of feedlot runoff often relies on sedimentation techniques; thus, accurate knowledge of feedlot runoff physical properties is required. This study characterized the physical and chemical properties of runoff effluent from earthen and concrete beef feedlots in Iowa with the objective of providing the necessary information to improve solid settling basin design and performance. Results, although not statistically significant ($p = 0.11$), indicated that solids in runoff from concrete lots tended to settle more slowly than solids from earthen lots. Particle size distribution and particle density measurements indicated that the poorer settleability of concrete lot runoff was primarily caused by lower particle densities: 1.47 ±0.17 g cm-3 (average ± SD) for concrete lots as compared to 1.89 ±0.11 g cm-3 for earthen lots. Runoff composition was analyzed before and after settling to relate nutrient reduction to solids removal. Results indicated an average of 41 g total Kjeldahl nitrogen per kg total solids and 16 g total phosphorus per kg total solids were removed during settling.

Keywords

Feedlot runoff, Particle density, Particle size, Runoff effluent, Settleability, Settling

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Comments

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Design of runoff control systems for beef feedlots requires an understanding of the chemical and physical properties of the runoff effluent (Gilbertson and Nienaber, 1973). Knowledge of these properties provides the primary information necessary to design effective waste management systems for feedlot runoff control, including both traditional containment systems and alternative technologies, such as vegetative treatment systems (VTSs). Better knowledge of the chemical and physical properties of runoff effluent would allow engineers to better predict how the effluent would be modified, both in quantity and quality, by different treatment components. For instance, sedimentation techniques, in the form of solid settling basins (SSBs), are often used as the primary treatment component in beef feedlot runoff control systems. Specifically, knowledge of the physical properties of runoff effluent could be used to improve the efficiency of SSBs, thereby increasing the performance of the subsequent treatment system components.

Settling characteristics could be predicted by applying Stokes's law to particles in the runoff; however, information on physical characteristics of the effluent, including particle densities and particle sizes, would be required. Gilbertson and Nienaber (1973) determined particle densities of solids in runoff effluent from a beef feedlot. They found the average particle density in feedlot runoff from an earthen lot to be 1.95 ±0.18 g cm^{-3} (average ±SD). Their findings indicated that as particle size decreased, particle density increased and volatile solids content decreased. Gilbertson and Nienaber (1973) did not measure the nutrient content associated with different particle sizes in their study; thus, the effect of sedimentation on effluent chemical quality cannot be predicted. Similarly, Chang and Rible (1975) studied the nutrient content of different particle sizes of beef feces; however, they did not study particle settleability.

Several studies (Gilbertson and Nienaber, 1973; Lott et al., 1994; Moore et al., 1973) have investigated the settling characteristics of solids in feedlot runoff effluent. Lott et al. (1994) and Moore et al. (1973) used laboratory experiments to measure the settling rate of solids in the runoff effluent from earthen feedlots, while Gilbertson et al. (1972) and Gilbertson and Nienaber (1973) used a combination of laboratory and field studies. Gilbertson and Nienaber (1973) found that the initial settling rate, up to a time of approximately 1 h, was very rapid; however, after this time, the rate of settling greatly decreased. Moore et al. (1973) recommended that a retention time of 10 min be used in the design of sedimentation basins. Lott et al. (1994) found similar results, concluding that a settling time of 10 min would remove the rapidly settleable portion of solids in the feedlot runoff. However, a recent study of feedlot runoff in Iowa (Andersen et al., 2009) showed that solids and nutrient concentrations were substantially reduced by modifying basin outlets from passive to active management. Passively managed basins used the hydraulic characteristics of the feedlot and basin outlet structure to control releases and retention times. Actively managed basins had valves installed at the outlet to allow the producers to control releases from their basins and thereby control the hydraulic retention time. This possibly indicates

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that short, i.e., 10 min, retention time may not provide sufficient settling of solids in effluent.

A study by Moody et al. (2007) showed that runoff from a concrete lot had higher concentrations of suspended solids after treatment in a settling basin than the effluent from earthen feedlots. Iowa Department of Natural Resources personnel (Hruby, 2010) and engineers (Melvin, 2009) have also noted that many concrete feedlots have more difficulty achieving good solids removal in settling basins when compared to earthen lots. Therefore, runoff solids from earthen and concrete feedlot may have significantly different settling characteristics.

The objective of this study was to determine the settling characteristics of solids in runoff from Iowa beef feedlots. Specifically, the difference in settleability of solids in runoff from earthen and concrete lots was evaluated to provide the required information to apply Stokes's law to model sedimentation. For the purpose of this article, settleability was defined as the extent and rate at which particles settle out of suspension. These objectives were met by measuring particle densities and effective particle size distributions for multiple runoff events from six Iowa feedlots. Additionally, chemical characteristics of the runoff effluent, both before and after settling, were measured to determine the impact of settling on nutrient removal.

Methods and Materials

Feedlot Descriptions

In this study, feedlot runoff from both concrete and earthen lots was collected and analyzed to characterize the chemical and physical properties of the runoff effluent. The runoff effluent was collected from six Iowa feedlots (three concrete lots and three earthen lots). Samples were collected from each lot during multiple rainfall events. Figure 1 shows a map of the feedlot locations. Feedlot descriptions and the number of rainfall events sampled for each feedlot are shown in table 1. Northwest Iowa 1, Central Iowa 1, and Southwest Iowa 1 were all earthen feedlots. Northwest Iowa 2 was a true concrete lot. Northeast Iowa 1 and Central Iowa 2 were hybrid lots, i.e., the lots were partially concrete but had portions that were earthen. The hybrid lots were considered as concrete for the purpose of this study, as all samples from the hybrid lots were collected from areas in the feedlot where the contributing drainage area consisted of only concrete surfaces. Effluent samples were collected just prior to the runoff reaching the solid settling basin. Runoff samples were collected during rainfall events and were brought to Iowa State University campus for analysis.

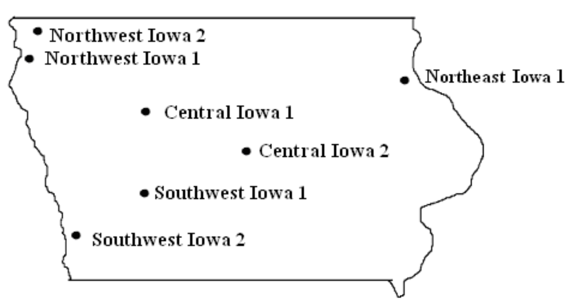

Figure 1. Map of feedlot locations sampled in this study.

Table 1. Summary of feedlot descriptions and number of rain events sampled for each location.

Site	No. of Cattle	Lot Type	Drainage Area (ha)	SSB (m^3)	Rain Events Sampled
Central Iowa 1	1,000	Earthen	3.09	4,290	3
Central Iowa 2	650	Hybrid	1.07	560	3
Northwest Iowa 1	1,400	Earthen	2.91	3,710	3
Northwest Iowa 2	4,000	Concrete	2.96	1,120	5
Southwest Iowa 1	2,300	Earthen	7.49	11,550	2
Northeast Iowa 1[a]	150	Hybrid	0.20	--	1

[a] Cow-calf operation; cows were on lot for approximately 3 h per day.

Experimental Procedure

Settling characteristics were determined using a method similar to that of Gilbertson and Nienaber (1973). Each runoff sample was agitated and poured into 1 L graduated cylinders. Ten milliliter subsamples were collected from a depth of 5 cm below the liquid surface at 0, 2, 4, 8, 16, 24, 48, 72, 96, 120, 144, and 168 h after cylinder agitation. The subsamples were analyzed for total solids content. The settling rate for each sample was determined by fitting a decaying exponential equation (eq. 1) to the total solids concentrations obtained in the 1 L cylinder settleability experiment for each sample as a function of time. Equation 1 was based on Brach-Papa et al. (2006) and assumed that the removal of settleable solids follows a first-order decay process. Parameter values were estimated by performing a least squares regression to fit the nonlinear equation to the observed data:

$$\mathrm{TS} = A \exp(-Bt) + C \quad (1)$$

where A represents the initial concentration of settleable solids, B represents a time constant related to the distribution of particle settling rates of the feedlot runoff solids, C represents the concentration of non-settleable solids, and t represents the settling time (h). For the purpose of this study, settleable solids were the initial total solids (TS) content minus the final TS content of the sample after a seven-day settling period. The inverse of B represents the time required, in hours, to remove 63% of settleable solids in the feedlot runoff. The B value was tested for normality (Shapiro-Wilk test) and homogeneity of variances (Bartlett's F test). Results indicated that the data were significantly non-normal. The B parameter was log-transformed, and then normality and homogeneity of variances were checked again. An analysis of variances was performed on the log-transform of the B parameter using the GLM procedure of SAS 9.2. Analysis was performed as a single-factor ANOVA with lot location as a fixed factor. An SAS estimate statement was used to assess the difference between earthen and concrete lots.

Particle density was determined on the solids collected during the cylinder tests. The settled solids were collected, dried for 24 h at 105°C, and ground in a Wiley mill (model 4, Thomas Scientific, Swedesboro, N.J.) to pass a 2 mm screen. A representative subsample was then collected, and the mass was determined using a balance (0.1 mg precision). The volume of the subsample was determined using a pycnometer (Flint and Flint, 2002). For this study, hexane was used in place of water when using the pycnometer. The hexane prevented lighter particles found in runoff effluent from floating during the analysis and affecting the volume measurements (Weindorf and Wittie, 2003). The particle density was calculated based on the measured mass and volume. The data were analyzed for normality using the Shapiro-Wilk test and homogeneity of variance using Bartlett's F test. The data were log-transformed to improve homogeneity of variance. A statistical analysis was performed on the log-transformed particle density using the GLM procedure of SAS 9.2. The analysis was performed as a single-factor ANOVA using lot location as a fixed factor. An SAS estimate statement was used to assess the difference in particle density between earthen and concrete lots.

Effective particle size diameters were calculated using Stokes's law (eq. 2) (Tchobanoglous et al., 2003). In order to use this version of Stoke's law, laminar flow is required. According to Crites and Tchobanoglous (1998), particle diameters 200 μm and smaller with a particle density of 2.65 g cm^{-3} should produce a Reynolds number less than one (laminar flow conditions). Since 98% of calculated effective particle diameters met this criterion, it was assumed that Stoke's law (eq. 2) was valid for this study:

$$D = \sqrt{\frac{18 V_s \mu}{g(\rho_p - \rho_l)}} \tag{2}$$

where D is the effective diameter of the particle (m), V_s is the settling velocity of the particle (m s^{-1}), μ is the viscosity of the fluid (kg m^{-1} s^{-1}), g is acceleration due to gravity (m s^{-2}), ρ_p is the particle density (kg m^{-3}), and ρ_l is the fluid density (kg m^{-3}). Settling velocity was calculated based on the sampling depth and the time of sample collection. Effective particle diameters were calculated using equation 2, the measured particle density, the calculated settling velocity, and by assuming that the viscosity and density of the runoff effluent were the same as for water. Effective particle size distributions were constructed for each sample based on the calculated effective particle size and the percent of settleable solids remaining in suspension. The data were analyzed for normality using the Shapiro-Wilk test, if the normality test failed, the data were log-transformed to achieve a normal distribution. The Bartlett F test was also run to test for homogeneity of the variance. A statistical analysis was performed on the log-transform of the d_{50} (50% of settleable solid particles diameters were smaller and 50% were larger in the size) of the settleable solids using the GLM procedure of SAS 9.2. The analysis was performed as a single-factor ANOVA using lot location as a fixed factor. An SAS estimate statement was used to assess the difference in median particle size of earthen and concrete lots.

Along with the physical settling data, chemical data were also collected. Before samples were processed to obtain physical settling data, subsamples of the runoff effluent from each sample were analyzed for total solids (TS), volatile solids (VS), total suspended solids (TSS), total phosphorus (TP), dissolved reactive phosphorous (DRP), total Kjeldahl nitrogen (TKN), ammonia-nitrogen (NH_3-N), and pH in the Agricultural Waste Management Lab at Iowa State University. The effluent was then allowed to settle for seven days in 1000 mL cylinders. The supernatant from the cylinder settling test was then tested for all the same parameters as the initial sample, except pH. These data allowed calculation of effluent quality improvement during sedimentation. The chemical methods used were: TKN (standard method 2001-11; AOAC, 2000), ammonia (NH_3) (standard method 4500-NH4B&C; APHA, 1998), dissolved reactive phosphorus (standard method 4500-P E; APHA, 1998), total phosphorus (method 965.17, photometric method; AOAC, 2000), pH using a water extraction technique and an electrode, total solids/moisture content and volatile solids (standard method 2540 G), and total suspended solids (standard method 2540 D). The data were analyzed for normality using the Shapiro-Wilk test. If the normality test failed, the data were log-transformed to achieve a normal distribution. Bartlett's F test was run to test for homogeneity of the variance. A statistical analysis was performed on the log-transform of the concentration data using SAS 9.2. The data were analyzed as a two-factor ANOVA using lot location and treatment, i.e., pre- and post-settling, as fixed factors. An estimate statement was used to assess the difference between earthen and concrete lots both before and after settling.

Nutrient removal factors for each of the measured constituents were developed using the pre- and post-settling concentrations. These factors were calculated by subtracting the average before and after concentrations of VS, DRP, TP, NH_3-N, TKN, and TSS and dividing each of them by the difference in average TS concentrations before and after settling for each site. The TS value was multiplied by 1000 to convert to g of constituent removed per kg of solids settled. The site factors were then averaged to get an overall average nutrient removal factor for all the feedlots used for this study.

Results and Discussion

Overall, the results failed to detect a statistically significant difference in settling characteristics between runoff samples collected from earthen and concrete lots; however, it appeared that solids in concrete effluent generally settled more slowly. On average, effluent from earthen lots settled 40% faster than effluent from concrete lots. However, similar reductions in total solids could be achieved for both lot types. Further investigation showed that the primary cause for slower settling was the smaller particle density of concrete runoff solids as opposed to smaller particle diameters, with no differences in medium particle diameter between earthen and concrete lots. Additionally, hindered settling was observed in several concrete lot runoff samples. The results are discussed in detail below.

Physical Characteristics

Feedlot Runoff Settling Rates

A statistical analysis was performed on the log-transform of the B parameter from equation 1 using the GLM procedure of SAS 9.2. The analysis was performed as a single-factor ANOVA with lot location as a fixed factor. An SAS estimate statement was used to assess the difference between earthen and concrete lots. Statistical analysis did not show a significant difference in settling rates between earthen and concrete lots ($p = 0.11$); however, the non-significance may have been due to the sampling of natural rainfall events rather than performing a highly controlled experiment using a rainfall simulator. Failure to detect a significant difference was likely a result of the high variability of settling rates within each site and the high variability in the rainfall events sampled. This was expected, as Gilbertson and Nienaber (1973) reported similarly high within-site settling rate variability, presumably due to the variation in sediment transport inherent due to variations in natural rainfalls. Alternatively, failure to de-

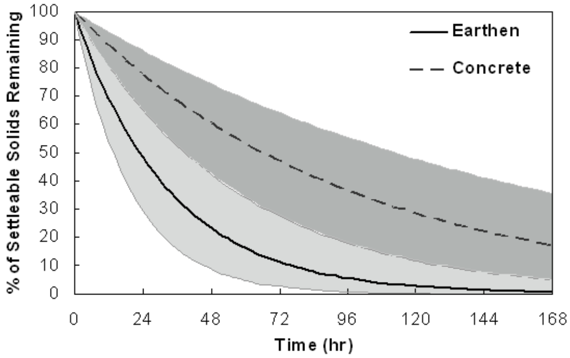

Figure 2. Comparison of average settling rates for earthen and concrete lots (measured data scaled to represent settling performance in a 1 m deep basin). Shaded areas represent one standard error of the mean.

tect a significant difference could have been caused in part by two of the three concrete lots in this study being hybrid, i.e., the lots had earthen sections rather than being entirely concrete. Since the hybrid lots were not scraped prior to the rainfall event and sampling for this study, cattle were allowed to track soil into the concrete lot section that would not have been present if the lot was entirely concrete (see the following Particle Density section for further discussion). Support for this hypothesis was provided by the fact that Northwest Iowa 2, the only entirely concrete lot, exhibited significantly slower settling than all the earthen lots but not the hybrid lots.

Figure 2 shows the difference in settling rates for earthen and concrete lots. This graph was developed using equation 1 and measured data and scaled to represent settling performance for a 1 m deep solids settling basin. Appropriate B values were calculated based on the averages values for the earthen and concrete lots. The shaded areas represent the standard error of the mean for each lot type. This figure shows that on average runoff from earthen feedlots settled 80% of settleable solids in 52 h, while concrete lots (including the hybrid sites) required 154 h to achieve similar settling results.

Particle Density

Runoff from concrete feedlots had a lower particle density when compared to earthen feedlot runoff ($p = 0.0004$). Earthen lots had an average particle density of 1.89 ±0.11 g cm^{-3} (average ±SD) compared to 1.47 ±0.17 g cm^{-3} for concrete lots. The particle density of earthen lots found in this study was comparable with the 1.95 ±0.18 g cm^{-3} found by Gilbertson and Nienaber (1973). Figure 3 shows the average particle densities for each of the six feedlots used in this study. A statistical analysis was performed on the log-transformed particle density using the GLM procedure of SAS 9.2. The analysis was performed as a single-factor ANOVA using lot location as a fixed factor. An SAS estimate statement was used to assess the difference in particle density between earthen and concrete lots. The true concrete feedlot, NW IA 2, was significantly different from all the earthen feedlots. The two hybrid concrete lots (Northeast IA 1 and Central IA 2) were not significantly different from Central IA 1 (earthen) but were significantly different from the other two earthen feedlots. This may have been due to the high variability of the Central IA 1 samples, the low replication (shown in table 1) of the Northeast Iowa 1, and the fact that Northeast IA 1 and Central IA 2 were hybrid lots.

Current publications (Tolle et al., 2007) have recommended using a particle density of 2.65 g cm^{-3} to predict the particle settling rate in feedlot runoff effluent; however, based on both this and the Gilbertson and Nienaber (1973) study, this value appears high. When Stokes's law was used to estimate the settling time using the new particle densities of 1.89 g cm^{-3} for earthen and 1.47 g cm^{-3} for concrete instead of the assumed 2.65 g cm^{-3}, the predicted settling velocities were reduced by 50% and 72%, respectively. These results indicate that the settling velocities were highly dependent on particle density. Therefore, basin design needs to account for this lower particle density. The measured particle density for concrete lots was similar to that of organic matter, which is typically around 1.3 g cm^{-3} (Jury and Horton, 2004), which makes sense because concrete feedlot surfaces are composed mainly of manure (fresh and dried) and bedding materials. Earthen lots have a higher particle density due to the mixing of soil particles, which typically have particle densities of around 2.65 g cm^{-3} (Flint and Flint, 2002), with the manure and bedding materials. This fundamental difference in lot surfaces could be the biggest factor in the settling differences between the two lot types.

Effective Particle Diameters

A particle size distribution analysis was performed using effective particle diameters calculated based on the sampling times and the percent of particles remaining in the settling

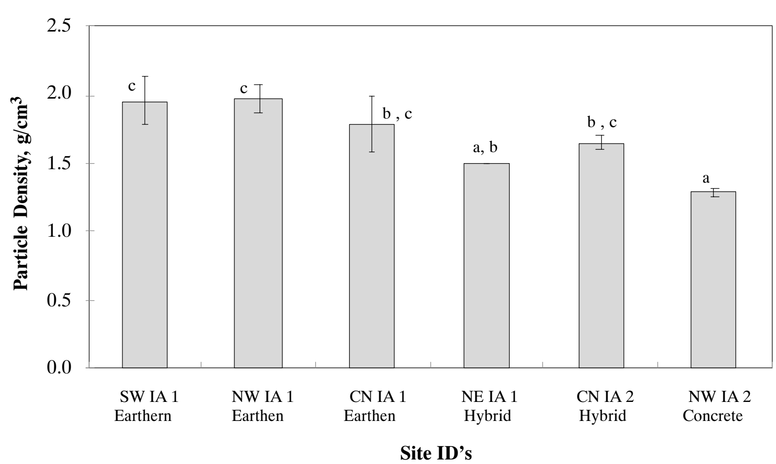

Figure 3. Average particle densities for each lot. Error bars represent standard deviations of particle density for the lot. Bars labeled with the same letters are not significantly different at α =. 0.05.

Table 2. Average concentrations (mg L^{-1}) of influent and effluent runoff samples.[a]

Sample	TS	VS	Ash	TSS	TP	DRP	TKN	NH_3-N
Influent	14,900	7,617	7,283	6,989	170	45	483	169
Standard error of the mean	2,818	1,535	1,283	2,018	30	12	100	41
Effluent	6,928	3,514	3,414	970	77	21	276	125
Standard error of the mean	1,310	708	602	280	14	6	57	30
Percent reduction	54	54	53	86	55	53	43	26
Standard error of the mean	7	7	11	11	8	13	8	13

[a] All influent concentrations were significantly different from effluent concentrations at $\alpha = 0.05$.

Table 3. Average reductions per kg of total solids reduced (standard errors of the mean of reductions are shown in parentheses).

Parameter	Reduction (g kg^{-1} TS)
Volatile solids	616 (71)
Dissolved reactive phosphorus	4 (1)
Total phosphorus	16 (3)
Ammonia	7 (4)
Total Kjeldahl nitrogen	41 (13)
Total suspended solids	920 (103)

tests. A statistical analysis was performed on the log-transform of the d_{50} (50% of settleable solid particles diameters were smaller and 50% were larger in the size) of the settleable solids using the GLM procedure of SAS 9.2. The analysis was performed as a single-factor ANOVA with lot location as a fixed factor. An SAS estimate statement was used to assess the difference in median particle size of earthen and concrete lots. Effective particle diameters from each of the lots were not significantly different with a p-value of 0.62. This was not unexpected, as particle sizes in feedlot runoff may be related to runoff rate. Because the size and intensity of rainfall was highly variable within a site, detecting a significant difference between sites was difficult. The average effective particle size distribution, pooled across all lots, is shown in figure 4. The *x*-axis shows the average effective particle diameter in μm, while the *y*-axis shows the percent of settleable solids finer than the specified diameter. Note that the *y*-axis only shows settleable solids, not total solids. Results showed that 98% of settled particles were smaller than 50 μm, i.e., silt sized.

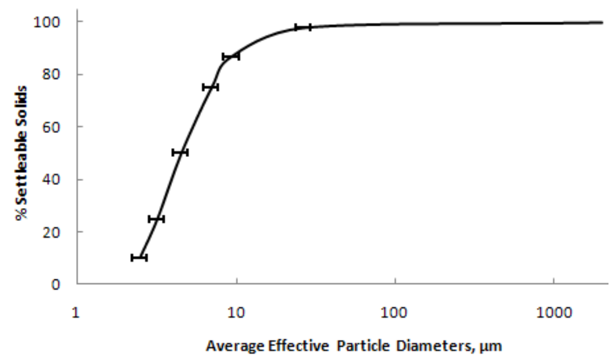

Figure 4. Average effective particle size distribution of settleable solids in runoff from feedlots in Iowa. Error bars represent standard errors of the mean.

A series of factors was developed to relate solids removal to nutrient removal. These factors were developed using the pre- and post-settling nutrient concentrations and are summarized in table 3. For example, this study found that on average 41 g TKN kg^{-1} TS were removed, while only 16 g TP kg^{-1} TS were removed. Additionally, very little NH_3-N or DRP removal and a large TSS removal were seen, indicating that the majority of the nutrient and contaminant removals were indeed caused by sedimentation. Also of note is that over half of all solids settled were organic in nature (VS), indicating that sedimentation offers a mechanism to substantially reduce effluent strength and a possibility to capture large amounts of nutrients.

Chemical Properties

In all cases, effluent concentrations were significantly reduced by settling the solids ($p < 0.001$). No significant differences between earthen and concrete lots were detected, either before or after settling; however, significant differences were recorded between sites. This most likely was due to the high variability between samples on a lot. The average concentrations, pooled across all lots, of the influent (feedlot runoff) and effluent (settled effluent) can be found in table 1. Similar average settled effluent concentrations were reported by Andersen et al. (2009) for Iowa feedlots with actively managed SSB outlets.

Average concentration reductions were approximately 50% for TS, VS, DRP, and TP. TSS concentrations were reduced by over 86%, as shown in table 2. Nitrogen reductions were less, with a 26% reduction in NH_3-N concentrations and a 43% reduction in TKN concentrations. Concentration reductions for earthen and concrete lots were similar for all parameters.

Conclusions

The physical and chemical parameters provided in this study could be used by engineers to improve sediment and nutrient removal efficiency in solid settling basins. This work provided the necessary elements to utilize a first-principle equation (Stokes's law) to estimate solid settling rates and sediment removal. Additionally, both physical and chemical properties were investigated, providing a link between nutrient and sediment capture in the solid settling basin. Although not quite significantly different, the results indicated that solids in runoff from concrete lots tended to settle more slowly than solids in earthen lot runoff. Further investigation showed that the slower settling for concrete lots (compared to earthen lots) was due to particle density, which was significantly different between the two lot types. Particle diameter differences between concrete and earthen lots were also tested and showed no significant difference.

This study indicated that, for a 1 m deep basin, a 2 to 4 day retention time would be required to remove 80% of settleable solids, while between 4 and 12 days would be required to achieve the same reduction for a concrete lot. This difference in settleability indicated a need for different design standards for earthen and concrete lot settling facilities. Because these long retention times may not be feasible, additional treatment components may be needed to further treat the runoff effluent.

Nutrient reduction factors were developed to estimate potential reductions per kg of TS removed during settling. This study found that, on average, 41 g TKN kg^{-1} TS and 16 g TP kg^{-1} TS were removed, and more than half of the solids removed for both earthen and concrete lots were volatile. Utilization of these factors will provide better insight into how best to size sediment basins to improve nutrient capture while still providing affordably sized solids settling basins.

Acknowledgements

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