2015

Development of a Turbidity Prediction Methodology for Runoff-Erosion Models

Sagar Neupane
Oklahoma State University

Jason R. Vogel
Oklahoma State University, jason.vogel@ou.edu

Daniel E. Storm
Oklahoma State University, dan.storm@okstate.edu

Bill J. Barfield
Oklahoma State University, bill@okstate.edu

Aaron R. Mittelstet
University of Nebraska-Lincoln, amittelstet2@unl.edu

Published in *Water, Air, & Soil Pollution* 226: 415 (2015), 14pp.; doi: 10.1007/s11270-015-2679-9
Submitted July 5, 2015; accepted November 6, 2015; published online November 13, 2015.

Development of a Turbidity Prediction Methodology for Runoff-Erosion Models

Sagar Neupane, Jason R. Vogel, Daniel E. Storm, Bill J. Barfield, and Aaron R. Mittelstet

Department of Biosystems and Agricultural Engineering, Oklahoma State University, Stillwater, OK 74078, USA

Corresponding author — J. R. Vogel, email jason.vogel@okstate.edu

Abstract

Surface water bodies can be impaired by turbidity and excessive sediment loading due to urban development, construction activities, and agricultural practices. Turbidity has been considered as a proxy for evaluating water quality, aquatic habitat, and aesthetic impairments in surface waters. The US Environment Protection Agency (USEPA) has listed turbidity and sediment as major pollutants for construction site effluent. Recently proposed USEPA regulations for construction site runoff led to increased interest in methods to predict turbidity in runoff based on parameters that are more commonly predicted in runoff-erosion models. In this study, a turbidity prediction methodology that can be easily incorporated into existing runoff-erosion models has been developed using fractions of sand, silt, and clay plus suspended sediment concentration of eight parent soils from locations in Oklahoma and South Carolina, USA.

Keywords: Turbidity, Suspended sediment concentration, Particle size distribution, Runoff-erosion models

1 Introduction

Urban development, construction activities, and agricultural practices contribute to increased sediment loading into rivers and lakes (USEPA 2009). Increased sediment loading increases the suspended sediment concentration (SSC) in the surface waters, which in turn often increases the turbidity levels in such water bodies. Turbidity is a light-scattering property of water and is often used as a relative measurement for water clarity (Parmelee and Ellms 1899; Kirk 1985; USEPA 1999; Davies-Colley and Smith 2001; ASTM 2011). The US Environmental Protection Agency (USEPA) has listed sediment and turbidity as primary pollutants for construction site effluent in 40 CFR Part 450, 2014 final rule (USEPA 2014). Turbidity may be used as a surrogate for other contaminants for determining the efficacy of best management practices (BMPs) for construction site effluent and erosion control, and can also have direct impacts on aquatic organisms. As a result, interest has increased in methods to predict turbidity using erosion-runoff models. The predicted turbidity can be a reference to evaluate impairments in surface water bodies.

The USEPA (2009) estimated that more than 40,000 km of streams, 4000 km^2 of lakes and reservoirs, and 600 km^2 of bays and estuaries are impaired by turbidity in the USA. Factors that have been shown to

impact the turbidity of water include soil type and concentration, organic content, color, nutrients, algae, and bacteria (Holstrom and Hawkins 1980; Gippel 1995; Davies-Colley and Smith 2001; Bilotta and Brazier 2008). The associated factors create water quality, aquatic habitat, and aesthetic impairments in surface water bodies.

Relationships have been documented between turbidity and many pollutants, including total nitrogen (Kim and Furumai 2013), particulate organic nitrogen and carbon (Slaets et al. 2014), total phosphorus and total suspended solids (TSS) (Jones et al. 2011; Ruzycki et al. 2014), mercury (Ruzycki et al. 2011), polycyclic aromatic hydrocarbons (PAHs) (Rügner et al. 2014), pathogens (USEPA 1999; LeChevallier and Norton 1992; Brookes et al. 2005; Johnson et al. 2010), and various indices of aquatic habitat quality (Lloyd 1987; Kirk 1991; Henley et al. 2000; Bilotta and Brazier 2008; Hazelton and Grossman 2009). Besides water quality and aquatic habitat, turbidity has been often reported as an indicator of surface water's aesthetic appearances. Aesthetic quality of surface waters is mainly related to public visual perception based on the clearness of water. Pflüger et al. (2010) demonstrated that the public had the lowest preference for rivers where turbidity and SSC are high. Similarly, the relationship between degraded aesthetic quality of surface waters and suspended sediment or turbidity has been reported in the literature (Effler et al. 1992; Smith et al. 1995; Bernal et al. 1999; Bilotta and Brazier 2008).

Turbidity has been used to estimate SSC (Rügner et al. 2013; Ruzycki et al. 2014). Parmelee and Ellms (1899) used measured turbidity to estimate SSC using a platinum and copper wire as an indicator of turbidity. Since then, many others have utilized regression techniques to predict SSC from turbidity including Gippel (1995), Lewis (1996), Wass et al. (1997), Riley (1998), Brasington and Richards (2000), Sun et al. (2001), Zabaleta et al. (2007), Gao et al. (2008), Minella et al. (2008), Williamson and Crawford (2011), Marttila and Kløve (2012), and Line et al. (2013). In these studies, the SSC-turbidity relationships are mostly linear at low turbidity levels, with non-linear SSC-turbidity relationships reported for higher turbidities or in heterogeneous soil mixes. Several site-specific SSC-turbidity relationships and evaluation comparisons (R^2) are documented in the literature (Rügner et al. 2013; Slaets et al. 2014). In some regression models, SSC along with the known fraction of sand, silt, and clay has been utilized as a predictor variable for turbidity (Holliday et al. 2003; Patil 2010; Perkins et al. 2014).

Existing runoff-erosion models may be applied to easily estimate SSC and particle size distribution (PSD) but have limited capabilities to predict runoff turbidity. In the USA, the Sediment, Erosion and Discharge by Computer Aided Design (SEDCAD) (Warner et al. 1998), the Sedimentology by Distributed Modeling Techniques (SEDIMOT) (Barfield et al. 2006), and SEDPRO (Harp et al. 2008) models are commonly used runoff-erosion models for predicting sediment in construction site runoff and designing sediment control BMPs (Hoomehr and Schwartz 2012). Warner and Sturm (2002) mentioned that SEDCAD 4 (the current version) can estimate SSC and PSD of runoff. They developed turbidity-SSC relationships for a few sediment control measures based on modelpredicted SSC for runoff samples; however, their relationship does not address the effect of PSD on turbidity prediction. SEDIMOT III evaluates construction site sediment control BMPs (Barfield et al. 2006). The SEDIMOT III and SEDPRO models have the capability to differentiate parent soil particles in five groups (sand, silt, clay, large aggregates, and small aggregates) based on Foster et al. (1985) soil matrix particle size distributions. However, SEDIMOT III and SEDPRO do not currently have the ability to predict turbidity of construction site runoff.

Pavanelli and Bigi (2005) mentioned that turbidity values vary significantly with changes in particle size distribution, even at similar SSC levels. Similarly, Slaets et al. (2014) demonstrated that turbidity varied significantly by changing the suspended sediment PSD at the same SSC. Gippel (1995) showed that clay-dominated SSC can increase turbidity up to four times more than the silt-dominated SSC. The amount of sand, silt, and clay (called primary particles) in the soil or runoff controls the turbidity, which is commonly determined by dispersing the soil or sediment with a dispersing agent (ASTM 2007). Besides primary particles, fractions of large and small aggregates are also found in undispersed soil or sediment. Quantification of such fractions using the method of Foster et al. (1985) requires large computations and

approximations for several parameters; therefore, this method has not been widely implemented. Since runoff sediment is mostly found in the undispersed form in nature, field turbidity measurements are mostly related to the undispersed form of sediment, whereas most current models predict turbidity based on the SSC and PSD in the dispersed form. Therefore, in order to predict the turbidity from parameters that are predicted by existing runoff-erosion models, the relationship between dispersed and undispersed PSD, and turbidity needs to be developed. Only then can a turbidity prediction methodology be easily integrated into runoff-erosion models.

The primary goal of this study is to develop a turbidity prediction methodology that is easily incorporated into existing runoff-erosion models. The two main objectives for this study are (1) to develop a simple, reliable method to predict dispersed turbidity and (2) to develop a simple, reliable method to predict undispersed turbidity. This paper presents the general methodology for dispersed and undispersed runoff turbidity prediction. The proposed methodology was calibrated for eight parent soils from Oklahoma and South Carolina, USA. If existing models can be utilized to predict turbidity based on SSC and PSD, there may be potential to correlate turbidity to water quality, habitat potential, and aesthetic appearances of the surface waters.

2 Materials and Methods

To predict undispersed runoff turbidity for a given parent soil, a systematic approach has been developed (Figure 1). The detail description of systematic approach has been described in subsequent sub-sections.

2.1 Soil Location and Characteristics

In this study, five parent soil samples (Kamie B, Norge B, Stephenville, Port A, and Port B) from Oklahoma and three parent soils (Cecil C, Cecil B, and Pacolet E) from South Carolina were selected based on availability from active construction sites in each area (Table 1). The parent soils represent a wide range of particle size distributions and soil horizons from two different areas of the USA but are not meant to represent an exhaustive list of soils. The alphabetical character following these soil names describes the soil horizon. These parent soils were selected from active construction sites during the sample collection period. Figure 2 shows the general distribution in Oklahoma and South Carolina of the soil series used in this study, and the exact county of soil sample collection is shown in Table 1.

A portion of all collected parent soils (2-3 kg of homogeneously mixed, air-dried for 2-3 weeks) were prepared using the classical coning and quartering method (Gerlach and Nocerino 2003) for PSD. The PSD was determined using the sedimentation method called pipette analysis (Gee and Bauder 1986) for Oklahoma soils, whereas PSD of South Carolina soils was obtained from Patil (2010) hydrometer analysis based on ASTM (2007). Fractions of sand, silt, and clay for each of the eight soils obtained from pipette or hydrometer analysis were characterized according to USDA soil textural classification criteria (Soil Survey Division Staff 1993) (Table 1). USDA soil textural criteria classify sand as 2 to 0.05 mm, silt as 0.05 to 0.002 mm, and clay as less than 0.002 mm. All parent soils' PSDs were site-specific measurements. Based on the soil formation, there were three general groups for studied parent soil series. The Port, Kamie, and Norge soil series were formed from Pleistocene age loamy alluvium deposits (NCSS 2000, 2004a, b); Stephenville soil series were formed by weathering Permian age sandstone (NCSS 2014), and Cecil and Pacolet soil series were formed from weathered igneous and metamorphic rocks (NCSS 2007, 2008).

2.2 Predictive Relationships for Turbidity

In this study, linear and power relationships between turbidity and SSC were investigated. Turbidities of each suspended sediment particle classes (clay, silt and sand) in the linear relationship are defined as

$$\begin{aligned} DT_{\mathrm{L,cl}} &= k_{1\mathrm{L}}[Clay] \\ DT_{\mathrm{si}} &= k_{2\mathrm{L}}[Silt] \\ DT_{\mathrm{sa}} &= k_{3\mathrm{L}}[Sand] \end{aligned} \tag{1}$$

where, $DT_{\mathrm{L,cl}}$, $DT_{\mathrm{L,si}}$, and $DT_{\mathrm{L,sa}}$ are the turbidities due to clay, silt, and sand, respectively, in dispersed suspended sediment water samples in nephelometric

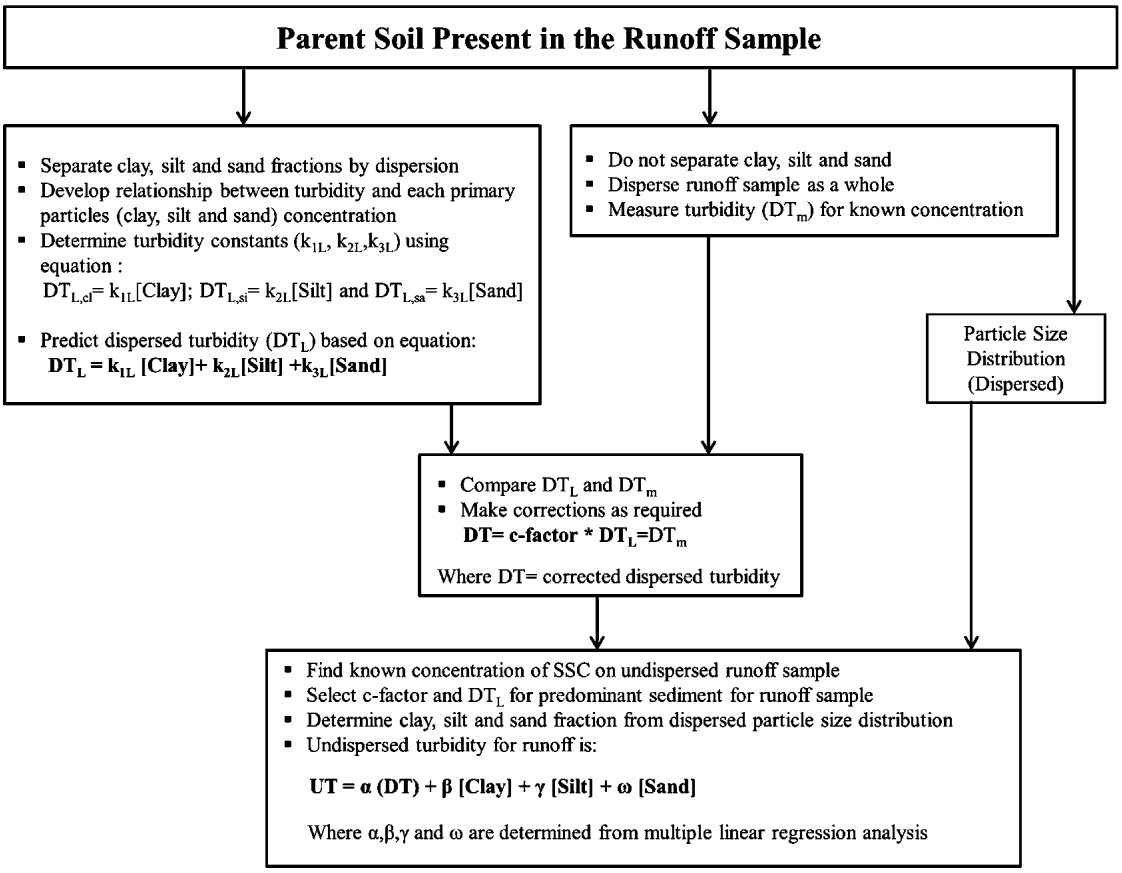

Figure 1. Flowchart for predicting undispersed turbidity based on suspended sediment concentration and particle size distribution for a given soil. $DT_{L,cl}$, $DT_{L,si}$, and $DT_{L,sa}$ are turbidities due to sand, silt, and clay in dispersed suspended sediment water samples in nephelometric turbidity unit (NTU); [*Clay*], [*Silt*], and [*Sand*] are concentrations of suspended sand-, silt-, and clay-sized sediment in milligrams per liter, respectively; and k_{1L}, k_{2L}, and k_{3L} are turbidity coefficients (NTU-l/mg) for sand, silt, and clay in the linear relationship, respectively. DT_L is dispersed turbidity in linear relationship and DT_m is measured undispersed turbidity; c-factor is correction factor obtained from Table 4. Similarly, UT is turbidity for undispersed soil (NTU); [*Clay*], [*Silt*], and [*Sand*] are dispersed suspended sediment concentrations; α is dispersed turbidity constant (unitless); β, γ, and ω are concentration factor (NTU-l/mg) for clay, silt, and sand.

Table 1. Results of site-specific measurements for percent of sand, silt, and clay with soil type of textures

Soil type	County of collection	Horizon depth range (cm)	Sand (%)	Silt (%)	Clay (%)	Texture
Kamie B	Tulsa County, OK	46-142	77	15	8	Sandy Loam
Norge B	Payne County, OK	46-168	63	17	20	Sandy Clay Loam
Port A	Noble County, OK	23-69	13	55	32	Silty Clay Loam
Port B	Noble County, OK	69-107	27	36	37	Clay Loam
Stephenville B	Payne County, OK	97-213	42	25	33	Clay Loam
Cecil B	Greenville County, SC	20-107	58	20	22	Sandy Clay Loam
Cecil C	Greenville County, SC	127-203	58	17	25	Sandy Clay Loam
Pacolet E	Greenville County, SC	8-74	52	24	24	Sandy Clay Loam

Classification was based on USDA textural soil classification criteria (Soil Survey Division Staff 1993). The letters on the soil type indicate the soil horizon. Horizon depth sources: NCSS 2000, 2004a, b, 2007, 2008, 2014

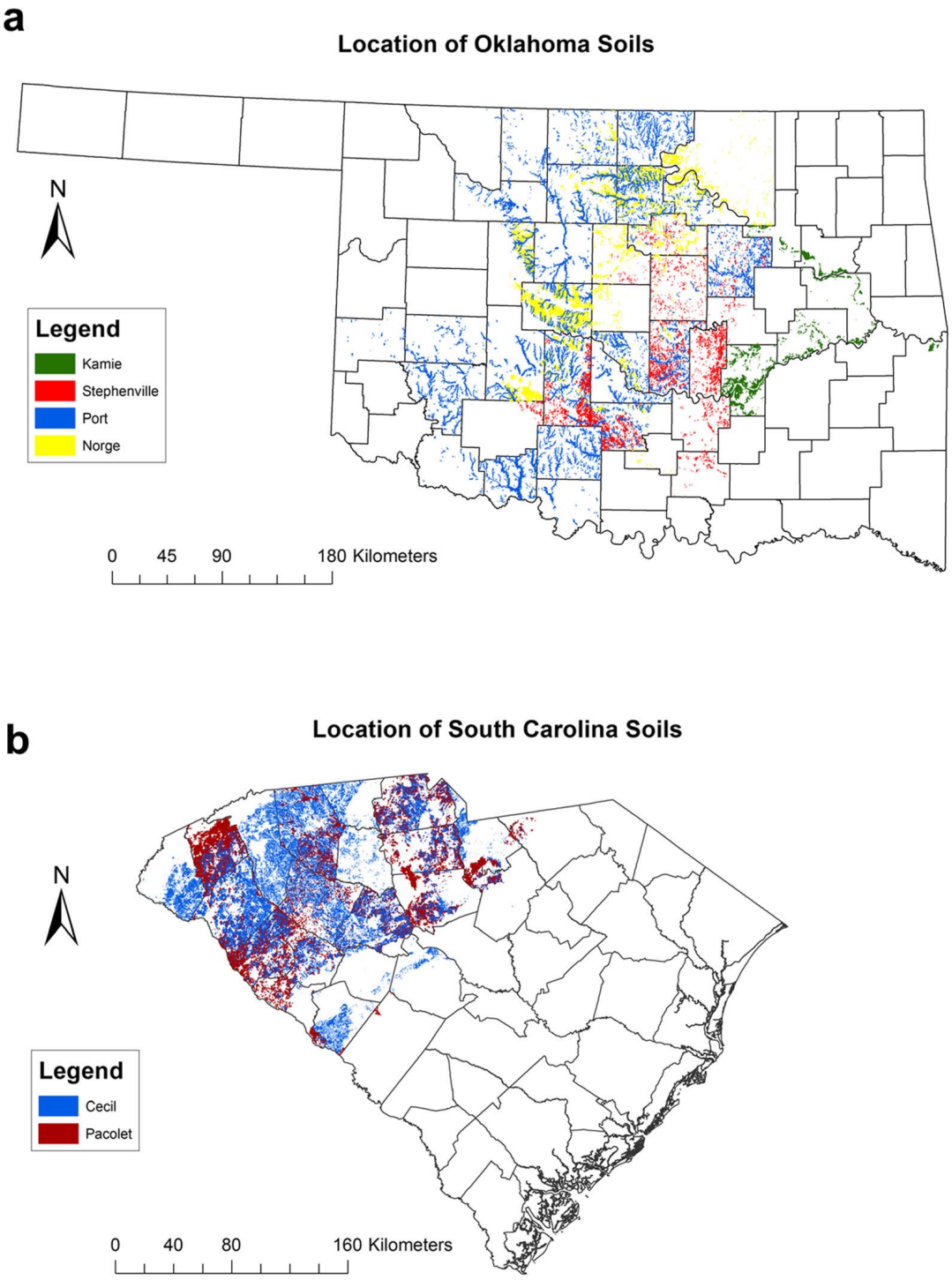

Figure 2. Study soil location map: **a)** studied soils distribution in Oklahoma, **b)** studied soil distribution in South Carolina (data source: Soil Survey Staff, 2011).

turbidity unit (NTU); [*Clay*], [*Silt*], and [*Sand*] are the dispersed suspended sediment concentrations of clay-, silt-, and sand-sized sediment, respectively, in milligrams per liter; and k_{1L}, k_{2L}, and k_{3L} are the turbidity coefficients (NTU-l/mg) for clay-, silt-, and sand-sized sediment, respectively, in the linear

relationship. The combined predictive linear relationship for dispersed turbidity is

$$DT_L = DT_{L,cl} + DT_{L,si} + DT_{L,sa} \quad (2)$$

Similarly, a second predictive relationship for dispersed turbidity is defined as non-linear power function (power relationship hereafter) between turbidity and each SSC particle-size class, which is defined as

$$DT_{P,cl} = k_{1P}[Clay]^a$$
$$DT_{P,si} = k_{2p}[Silt]^b$$
$$DT_{P,sa} = k_{3p}[Sand]^c \quad (3)$$

where $DT_{P,cl}$, $DT_{P,si}$, and $DT_{P,sa}$ are the dispersed turbidities due to clay-, silt-, and sand-sized sediment, respectively, in NTU in the power relationship, respectively, and k_{1P}, k_{2P}, and k_{3P} are the turbidity coefficients (NTU-l/ mg) for clay-, silt-, and sand-sized sediment, respectively. Similarly, a, b, and c are turbidity exponents clay-, silt-, and sand-sized sediment, respectively, in the power relationship. The combined predictive power relationship for dispersed turbidity is

$$DT_P = DT_{P,cl} + DT_{P,si} + DT_{P,sa} \quad (4)$$

Since a runoff sample would nearly always be in an undispersed form, a proposed predictive relationship for undispersed runoff turbidity is

$$UT = \alpha(DT) + \beta[Clay] + \gamma[Silt] + \omega[Sand] \quad (5)$$

where UT is the turbidity for undispersed soil (NTU); [*Clay*], [*Silt*], and [*Sand*] are the dispersed suspended sediment concentrations of clay-, silt-, and sand-sized sediment, respectively, in milligrams per liter; α is the dispersed turbidity factor (unitless); and β, γ, and ω are the concentration factors (NTU-l/mg) for clay-, silt-, and sand-sized sediment, respectively. DT is dispersed turbidity of the sample obtained from Equation (2) or (4) whenever applicable.

2.3 Laboratory Separation of Sand, Silt, and Clay

To separate the sand, silt, and clay fraction of each soil, 2-3 kg of homogeneously mixed, air-dried parent soil was collected using the classical coning and quartering method for homogeneous mix (Gerlach and Nocerino 2003). The sample was then sieved through a 2-mm opening, ASTM No. 10 sieve (ASTM 2013) to remove gravel-size and larger particles. As per ASTM (2007), the sample passing through the No. 10 sieve was then soaked with 125 ml sodium hexametaphosphate (SHMP) solution (40 g/l concentration) per 50 g of soil sample for 16 h to disperse the soil particles. After the soaking period, the sample was sieved through a No. 270 sieve (53-μm opening) to remove sand-sized particles, resulting in silt- and clay-sized particles only. Note that the soil passed through No. 270 sieve is the portion of silt and clay according to the USDA classification (50 μm, cutoff for silt and clay), which is a different sieve size specification than described by ASTM (2007). During the sieving process, 40 g/l SHMP solution was used instead of water to maintain a constant 40 g/l concentration of SHMP in silt and clay slurry. The retained sample (sand) on the No. 270 sieve was washed with reverse osmosis (RO) water five to six times to minimize the SHMP residuals present. The sand portion was oven-dried at 90°C to constant mass in a preweighed polypropylene jar. The organics and minerals present in the soil sample may affect the turbidity of soil sample; therefore, a lower temperature than the ASTM (2007) recommendation of 110°C was used for sample drying to prevent combustion or volatilization of any organic matter present. The organic matter content present in the soil sample was not measured.

Since separation of silt cannot be separated from clay by sieve analysis, a centrifugation method was utilized for this purpose. A Beckman GP centrifuge (Beckman Instruments 1988) was used to separate silt and clay from the sample. The soil slurry passed through the No. 270 sieve was divided into four 750-ml centrifuge bottles and centrifuged for 1 min and 42 s at 1000 RPM based on rotor's specifications of Beckman Coulter (2007) and using the relationship developed by Hathaway (1956). After centrifuging, the bottles were carefully removed from the centrifuge and approximately 80 % of the supernatant was decanted from each bottle. This decanted volume was transferred to preweighed polypropylene jars for oven drying at 90 °C to constant mass. The particles in the decanted portion were clay-sized particles and SHMP (40 g/l concentration), which made a hard clod after drying. Clay and SHMP were broken up using an electric spice grinder (Warning Commercial WSG30, CT, USA), resulting in final product of powdered clay and SHMP.

The SHMP concentration and resulting mass were recorded in each soil sample. The remaining 20 % soil slurry in the centrifuge bottles was mainly silt-sized

particles, a small amount of clay-sized particles, and SHMP. A sufficient amount of RO water was used to refill the bottles and mixed thoroughly, and the centrifuge run was repeated up to 13 times until there was a reasonably clear suspension (one can see objects across the sample bottle easily with the naked eye as shown in Figure 3) in the bottles to represent when all clay-sized particles had been removed by the SHMP slurry. The remaining soil slurry in the centrifuge bottle was silt, which had only a very small residual of SHMP as a result of the multiple decanting and dilutions. The silt slurry was transferred to pre-weighed polypropylene jars for oven drying at 90°C to constant mass.

2.4 Sample Preparation and Turbidity Measurement

Turbidity measurements were completed for each dispersed primary particle fraction (sand, silt, and clay) for each soil using a Hach Hydrolab MS5 Sonde (OTT Hydromet, CO, USA; called turbidity meter hereafter), which has a maximum reading of 3000 NTU. The turbidity meter was calibrated using Hach company's turbidity standard in four points (1, 100, 1000, and 3000 NTUs). Ranges of dispersed SSC concentrations (approximately 50, 100, 200, 400, 800, 1600, 3200, and 4000 mg/l) were selected for clay, silt, and sand in each type of soil to determine turbidity constants (Equation (1) and (3)) for clay, sand, and silt for each parent soil. Similarly, to test predictive relationship (Equations (2) and (4)), turbidity was measured for a range of combinations of sand, silt, and clay for each soil. The sand, silt, and clay combinations were random and ranged from 250 to 5000 mg/l concentration in total. For example, 48 mg of sand, 240 mg of silt, and 212 mg makes 500 mg of mix. There were a total of 16 such combinations for each soil types. The turbidity for each of these samples was measured in a 1-l beaker filled with 750 ml RO water plus the appropriate mass of soil placed on a continuous magnetic stirrer (Model: S131125, Thermo Scientific Cimarec, USA) rotating at a constant speed of approximately 525 rpm (level 7 on the stirrer) to keep solution in suspension. For clay, these concentrations were adjusted appropriately to account for SHMP content. The turbidity probe was inserted into the sample beaker as per turbidity meter specifications (Hach 2006), and turbidity readings were recorded every minute for up to 15 readings. The first 5 min was considered as mixing time, and median of the last five 1-min readings was considered as the turbidity of the sample. The methodology was adapted from USGS field protocol for turbidity, which explains the reported turbidity values as the median of three or more readings at ±10 % error range (Anderson 2005).

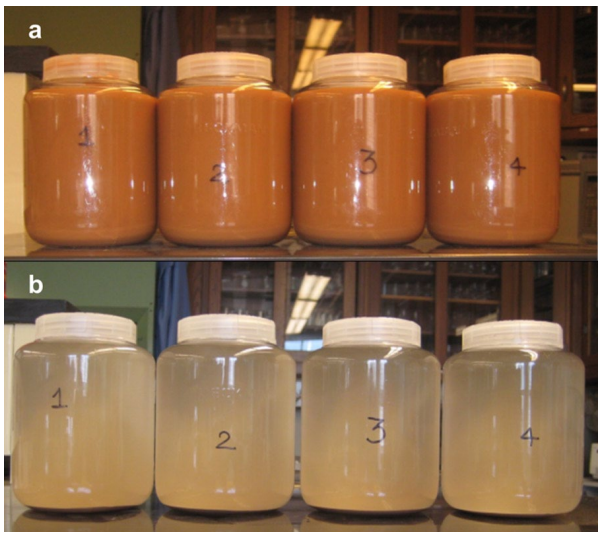

Figure 3. Samples in 750-ml centrifuge bottles: **a)** before the centrifuge runs **b)** after 13th centrifuge run, which were considered as clay-free samples.

For quality control, all measurements were completed for at least duplicate samples. If the second set of turbidity measurements was different than the first set (out of turbidity meter's error range, ±1 % for 0-100 NTU, ±3 % for 100-400 NTU, ±5 % for 400-3000 NTU), a third set of measurement was conducted. The process was repeated for all concentrations (each clay, sand, and silt fraction) of all eight soils.

To measure undispersed turbidity, separate soil samples (not used in dispersed turbidity measurement) were prepared for each of the eight parent soils. Approximately 250 g of oven-dried parent soil sample (oven-dried at 90°C to a constant mass) was collecting using the quartering and coning method (Gerlach and Nocerino, 2003). Clods larger than approximately 2 mm were ground using a rubber pestle in a mortar. The sample was then sieved through a No. 10 sieve to remove gravel-size particles and stored in an airtight container. From the sample container, two types of representative suspended sediment samples were created. The first type of sample contained consisted of the entire sample (sand, silt, and clay fractions), whereas the second type of sample was without sand (i.e., consisted of only the silt- and clay-sized sediment fractions) that was meant to approximate eroded particles.

For the first sample type, 12 sub-samples of different sediment mass (and therefore concentration) were prepared for the turbidity measurement in such that it represented low to high concentrations of suspended sediment (Kamie B, 473-5554 mg/l; Norge B, 285-4906 mg/l; Port A, 515-4139 mg/l; Port B, 429-4515 mg/l; Stephenville B, 421-6693 mg/l; Cecil B, 205-1433 mg/l; Cecil C, 304-4890 mg/l; and Pacolet E, 144-1045 mg/l). A known sediment mass was put into a 1-l beaker and 750 ml of RO water was added. The sample was continuously stirred with a magnetic stirrer (Thermo Scientific Cimarec) at speed 7 (about 525 rpm). This type of sample (without addition of SHMP) was termed as undispersed turbidity (UT). Turbidity was measured using the previously described techniques (taking the median of the last five readings of 15 one-minute turbidity measurements). These procedures were applied to all eight soils and samples. After 15 min (completion of turbidity measurement), 30 g of SHMP (to maintain 40 g/l concentration) was added and mixing with the magnetic stirrer was continued for 5 min, or until the SHMP crystals were completely dissolved. After SHMP addition, the sample was covered and stored at room temperature in a dark location for 16 h. Turbidity was then measured again. This type of sample was termed as measured dispersed turbidity (DT_m).These procedures were applied to all eight soils. The UT and DT_m samples were used for validating Equation (5) and used for the systematic procedure to predict runoff turbidity (Figure 1).

In addition to the parent soils, a second soil distribution meant to approximately represent the eroded suspended sediment distribution was analyzed for soil that was sieved through a No. 270 sieve to remove sand-sized particles. Turbidities were measured on six subsamples of this silt- and clay-only soil in such a way that concentrations ranged lower to higher (Kamie B, 430-5335 mg/l; Norge B, 550-1903 mg/l; Port A, 667-2928 mg/l; Port B, 624-2887 mg/l; Stephenville B, 583-5236 mg/l; Cecil B, 205-1433 mg/l; Cecil C, 536-1849 mg/l; and Pacolet E, 242-619 mg/l), with an upper turbidity slightly less than 3000 NTU, which represented the upper range of the turbidity meter. The turbidity measurements for the clay- and silt-only samples were similar as discussed above, and undispersed and dispersed turbidity measurements were completed similarly to the measurements for the first type.

2.5 Statistical Methods

Turbidity coefficients and exponents for Equations (1) and (2) were determined by Microsoft Excel (Microsoft 2010) regression trend line with the intercept term set to zero. The coefficients of determination (R^2) values were reported for those relationships. Based on the turbidity coefficient, exponent, and known concentration of [*Clay*], [*Silt*], and [*Sand*], turbidities for linear and power relationships were predicted. The predicted turbidities in such relationships were compared with measured turbidities with reference to *R*2, Nash-Sutcliffe efficiency (NSE), and absolute percentage relative error (RE in %) for all eight soils. The NSE value (Nash and Sutcliffe 1970) was computed as

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} (Tm_i - Tp_i)^2}{\sum_{i=1}^{n} (Tm_i - Ta)^2} \right] \quad (6)$$

where Tm_i is the measured turbidity in the *i*th sample, Tp_i is the predicted turbidity for the *i*th sample, *Ta* is the average turbidity of measured samples, and *n* is the number of sample. The relative percentage error (RE) was evaluated as

$$RE = \frac{\left| Tm_i - Tp_i \right|}{Tm_i} \times 100 \quad (7)$$

where Tm_i is the measured turbidity in the *i*th sample and Tp_i is the predicted turbidity for the *i*th sample.

To determine undispersed turbidity for runoff sample, the number of coefficients used in Equation (5) was minimized by determining the insignificant variables with multiple regression analysis using Minitab statistical software (Minitab 2010).

3 Results and Discussion

Methodologies for predicting the turbidity of dispersed and undispersed runoff samples have been developed. The coefficients and parameters for best fit predictive relationships [Equations (1) to (5)] were determined and undispersed runoff turbidities were estimated for the eight soils shown in Table 1.

Table 2. Turbidity constants for all soils as described in Equations (1) and (3)

Soil Type	Turbidity Constants														
	Linear						Power								
	Clay		Silt		Sand		Clay			Silt			Sand		
	k_{1L}[a]	R^2	k_{2L}[a]	R^2	k_{3L}[a]	R^2	k_{1P}[a]	a[b]	R^2	k_{2P}[a]	b[b]	R^2	k_{3P}[a]	c[b]	R^2
Kamie B	0.432	0.996	0.202	0.999	0.030	0.986	0.324	1.034	0.999	0.209	0.993	0.999	0.045	0.940	0.992
NorgeB	0.729	0.998	0.242	0.999	0.052	0.974	0.635	1.016	0.998	0.204	1.020	0.999	0.060	0.976	0.994
Stephenville B	0.578	0.987	0.256	0.999	0.056	0.997	0.340	1.063	0.998	0.202	1.028	0.999	0.050	1.003	0.998
PortA	0.595	0.995	0.354	0.998	0.036	0.992	0.379	1.063	0.999	0.285	1.024	0.999	0.038	0.998	0.995
PortB	0.659	0.996	0.232	0.999	0.091	0.998	0.453	1.042	0.999	0.209	1.010	0.999	0.103	0.984	0.997
CecilB	0.643	0.988	0.660	0.998	0.061	0.995	0.457	1.041	0.998	0.537	1.024	0.999	0.035	1.069	0.997
CecilC	0.777	0.998	0.490	0.998	0.035	0.988	0.597	1.037	0.999	0.359	1.042	0.997	0.070	0.914	0.993
PacoletE	1.432	0.992	0.742	0.998	0.088	0.959	1.695	0.972	0.992	0.507	1.046	0.999	0.049	1.061	0.976

The letter after the soil type represents the soil horizon. R^2 = coefficient of determination,
a. Turbidity coefficients (NTU-l/mg)
b. Turbidity exponents (dimensionless)

3.1 Turbidity Constants and Dispersed Turbidity-SSC Relationship Validation

For each dispersed primary particle type (clay, silt, and sand) and soil, the turbidity constants and coefficients for the linear and power relationships (Equations (1) and (3)) varied as shown in Table 2. This table describes the parameters for Equations (1) and (3); for example, for Kamie B soil, $DT_{L,cl} = 0.432$ [Clay] in the linear relationship and $DT_{p,cl} = 0.324$ [Clay]$^{1.034}$ for the power relationship. For all eight soils, the relationship between dispersed turbidity and SSC for each of the primary particle classes (clay, silt, and sand) was strong ($R^2 > 0.96$) for both the linear and power relationships. Since the R^2 did not give strong evidence that one type of relationship is better than the other, other statistical results were evaluated. Based on Equations (2) and (4) (parameters from Table 2), measured versus predicted turbidity values were compared with reference to R^2, Nash-Sutcliffe efficiency (NSE) value, and average relative error (RE, in %) for all eight soils and both relationships. Table 3 shows that the NSE value for the power relationship is greater than or equal to the linear relationship for

Table 3. Linear versus power model performance comparison in terms of coefficient of determination (*R*2), Nash-Sutcliffe efficiency (NSE), and percentage average relative error (RE)

Soil type	Linear			Power		
	R^2	NSE	RE (%)	R^2	NSE	RE (%)
Kamie B	0.996	0.94	9.1	0.996	0.98	4.6
Norge B	0.997	0.99	6.3	0.997	0.99	4.1
Stephenville B	0.996	0.96	14.4	0.997	0.99	5.6
Port A	0.996	0.94	13.8	0.996	0.98	7.3
Port B	0.996	0.99	12.1	0.997	0.99	4.6
Cecil B	0.994	0.99	5.9	0.994	0.99	6.7
Cecil C	0.978	0.98	4.9	0.978	0.98	6.9
Pacolet E	0.996	0.98	9.3	0.996	0.99	5.7

all eight soils, and REs were usually less in the power relationships (except Cecil B and Cecil C).

It is important to note that the turbidity meter has instrument error ±1% for 0-100 NTU, ±3% for 100-400 NTU, and ±5% for 400-3000 NTU. In addition to this, preparation and processing error may have also influenced turbidity measurements. The NSE and RE values showed that the power model has a smaller relative error; however, given instrument error, possible measurement errors, and precision goals of the study, a conclusion has been made that the linear model is sufficient for most uses. If site-specific soils performed better in the power relationship than the linear and project objectives require that level of accuracy, the power relationship can be used to predict turbidity. However, for our objectives, linear relationships are considered sufficient for dispersed turbidity prediction and used for undispersed turbidity prediction hereafter in this study.

3.2 Prediction of Undispersed Runoff Turbidity

The systematic approach has been followed to predict undispersed runoff turbidity for a given parent soil (Figure 1). The predicted dispersed linear turbidity (DT_L) and direct measurement of turbidity without separating primary particles (DT_m) were compared. The relationship between DT_L and DT_m was estimated using linear regression using Excel (Table 4). However, the intercept term in the linear regression equation was determined to be insignificant ($p < 0.05$) for all soils tested, so the equations are presented without the intercept. An intercept of zero is expected since the measured and predicted turbidity of pure water would be expected to both be zero.

The coefficient term in DT_L was considered as a dimensionless correction factor (called c-factor hereafter) and is used to adjust the turbidity predicted from turbidity constants for each individual particle-size class that were estimated from particles that were separated by centrifuging of the parent soil, to approximately match the turbidity actually measured with the dispersed parent soil without centrifugation. This c-factor adjustment is likely associated with potential changes in particle shape, size, and/or color during centrifuging. Studies have shown that turbidity can be affected by color and PSD of suspended sediment present in the water sample (Gippel 1995; Packman et al. 1999; Teixeira and Caliari 2005).

With reference to a known concentration of SSC for undispersed runoff samples, c-factor, DT_L, and primary particle fractions (Table 1), undispersed turbidity model factors were estimated using multiple linear regression analysis with Minitab statistical software (Minitab 2010). These equations (Table 5) were matched with the predictive Equation (5). The significant coefficients α, β, γ, and ω factors for Equation 5 were selected ($p < 0.05$). Model equations that utilize dispersed turbidity, siltfraction sediment concentration, and/or clayfraction sediment concentration are compared in Table 5. For all soils, the factor "ω" was insignificant (therefore considered zero) based on the regression analysis.

Table 4. Regression equations to predict dispersed turbidity (NTU) based on linear dispersed turbidity (NTU) and c-factor

Soil Type	Regression Equation	c-factor	R^2	p value
Kamie B	$DT = 1.31\ DT_L$	1.31	0.991	< 0.0001
Norge B	$DT = 1.50\ DT_L$	1.50	0.995	< 0.0001
Port A	$DT = 1.43\ DT_L$	1.43	0.984	< 0.0001
Port B	$DT = 1.28\ DT_L$	1.28	0.997	< 0.0001
Stephenville B	$DT = 1.50\ DT_L$	1.50	0.992	< 0.0001
Cecil B	$DT = 1.34\ DT_L$	1.34	0.976	< 0.0001
Cecil C	$DT = 1.73\ DT_L$	1.73	0.997	< 0.0001
Pacolet E	$DT = 1.23\ DT_L$	1.23	0.996	< 0.0001

The c-factor associated with change in dispersed turbidity between direct measurement and model prediction. p value (< 0.05) represents the significant relationship between corrected dispersed turbidity (DT) and predicted linear turbidity (DT_L)

Table 5. Undispersed turbidity model equations (related to Equation (5))

Soil type	Model	Undispersed turbidity (UT)	Model R^2	SE (NTU)	p value	
					Coefficients	
					b_1	b_2
Kamie B	1	UT = 1.39 *DT*−0.94 [*Clay*]	0.998	22	< 0.0001	0.021
	2	**UT = 1.18** [Clay]−**0.12** [Silt]	**0.998**	**22**	< **0.0001**	< **0.0001**
	3	UT = 0.63 *DT*	0.997	25	< 0.0001	—
Norge B	1	UT = 1.67 *DT*−1.95 [*Clay*]	0.999	20	< 0.0001	< 0.0001
	2	**UT = 0.45** [Clay]+**0.38** [Silt]	**0.999**	**20**	< 0.0001	< 0.0001
	3	UT = 0.56 *DT*	0.970	117	< 0.0001	—
Port A	**1**	**UT = 0.34** DT+**0.53** [Clay]	**0.990**	**113**	**0.02**	**0.02**
	2	**UT = 0.66** [Clay]+**0.25** [Silt]	**0.990**	**113**	**0.001**	**0.02**
	3	UT = 0.67 *DT*	0.986	130	< 0.0001	—
Port B	1	UT = 1.05 *DT*−0.43 [*Clay*]	0.997	60	< 0.0001	0.13
	2	**UT = 0.66** [Clay]+**0.20** [Silt]	**0.997**	**60**	< **0.0001**	< **0.0001**
	3	UT = 0.71 *DT*	0.996	62	< 0.0001	—
Cecil C	1	UT = 0.58 *DT*−0.02 [*Clay*]	0.992	29.5	< 0.0001	0.797
	2	**UT = 0.91**[Clay]+**0.38** [Silt]	**0.992**	**29.5**	< **0.0001**	< **0.0001**
	3	**UT = 0.57** DT	**0.992**	**28.7**	< **0.0001**	—
Cecil B	**1**	**UT = 2.52** DT−**3.58** [Clay]	**0.999**	**35**	< **0.0001**	< **0.0001**
	2	UT = 0.002 [*Clay*]+1.25 [*Silt*]	0.999	35	0.9720	< 0.0001
	3	UT = 0.66 *DT*	0.976	151	< 0.0001	—
Stephenville B	1	UT = 1.38 *DT*−1.05 [*Clay*]	0.997	59	< 0.0001	0.011
	2	**UT = 0.51** [Clay]+**0.24** [Silt]	**0.997**	**59**	< **0.0001**	< **0.0001**
	3	UT = 0.58 *DT*	0.995	70	< 0.0001	—
Pacolet E	**1**	**UT = 3.24** DT−**7.65** [Clay]	**0.996**	**81**	< **0.0001**	< **0.0001**
	2	UT = 0.32 [*Clay*]+1.45 [*Silt*]	0.996	81	0.094	< 0.0001
	3	UT = 0.64 *DT*	0.985	158	< 0.0001	—

The bold text in model column represents the good fit model to predict undispersed turbidity for a given soil. p value represents the level of significance at 0.05, UT is undispersed turbidity in NTU, *DT* is corrected dispersed turbidity in NTU, [*Clay*] and [*Silt*] are concentrations in milligrams per liter based on dispersed particle size distribution of the parent soil. SE represents standard error (NTU) and R^2 is coefficient of determination

For each soil, best fit model equations to predict undispersed turbidity for runoff samples were determined. The best-fit model equation, shown in bold for each soil in Table 5, was selected based on the values of p (< 0.05), R^2 (maximized), and SE (minimized). Model 1 (predictor variables: *DT* and [*Clay*]) had the best fit in Port A, Cecil B, and Pacolet E soils, while model 2 (predictor variables: [*Clay*] and [*Silt*]) had best fit for Kamie B, Norge B, Port A, Port B, Cecil C, and Stephenville B soils. Model 3 (predictor variable: DT only) was the best fit for only Cecil C soil among the eight soils analyzed. Best fit model selections depended upon the individual soil characteristics. Effect of particle size and shape for turbidity estimation has been previously reported on the several studies (Gippel 1995; Pavanelli and Bigi 2005; Teixeira and Caliari 2005). Holstrom and Hawkins (1980), and the results from this study indicate a decrease in turbidity with increase in predominant particle-size class (*D*50). Any inconsistencies in the model performances may be related with variations in runoff sample colors and organic matter present in the suspended sediment samples which were not considered in this study. Future research could explore the effect of color and variation of organic matters on turbidity prediction for runoff water.

4 Conclusions

The primary goal of this study was to develop a turbidity prediction methodology that can be easily incorporated into existing runoff-erosion models. To achieve this goal, a reliable method that uses the concentration of sediment in each primary particle fraction (sand, silt, and clay) has been developed to predict dispersed and undispersed turbidity. This method was applied to eight parent soils from Oklahoma and South Carolina, USA. For broader use, as with any empirical model, relationships between the concentration of sediment in each primary particle fraction and turbidity for specific soils must be calibrated and validated using the methodology provided. The runoff turbidity prediction methodology presented in this study can easily be used to develop turbidity coefficients for any soil and can be used as an add-on, predictive tool using currently available runoff-erosion models.

Once the presented methodology integrated and validated in existing runoff-erosion models, such as SEDMOT III, SEDPRO, and SEDCAD, turbidity can be predicted for runoff from disturbed landscapes including construction sites and tilled agricultural fields. Further, the proposed methodology can be potentially extended to make turbidity as an all-in-one surrogate measurement for evaluating and monitoring water quality, habitat potential, and aesthetic appearances for surface waters. However, future research is required to minimize the compounding error since the proposed methodology requires several predicted parameters. In addition to this, exploring color and small and large aggregates of runoff suspended sediment samples can provide more reliable estimation of undispersed turbidity for runoff samples.

Acknowledgments — This research was funded in part by the Oklahoma Department of Transportation Research Program, the Oklahoma Transportation Center, and Woolpert, Inc. The authors would like to thank Magen Kegley, Riley Jones, and Hanna Huling for assistance in data collection.

References

Anderson, C. (2005). Turbidity 6.7 (Version 2.1, 9/2005). In F. D. Wilde, ed., *National Field Manual for the Collection of Water-Quality Data, Book 9, Handbooks for Water-Resources Investigations; Chapter A6 Field Measurement*: U.S. Geological Survey.

ASTM. (2007). *ASTMD422-63 standard test method for particle-size analysis of soils*. West Conshohocken: ASTM International.

ASTM. (2011). *D7726-11 Standard guide for the use of various turbidimeter technologies for measurement of turbidity in water* (p. 17). West Conshohocken: ASTM International.

ASTM. (2013). *E11-13 Standard specification for woven wire test sieve cloth and test sieves*. West Conshohocken: ASTM International.

Barfield, B. J., Hayes, J. C., Stevens, E., Harp, S. L., & Fogle, A. (2006). SEDIMOT III model. In V. P. Singh & D. K. Frevert, eds., *Watershed models* (pp. 381–398). Boca: CRC Press.

Beckman Instruments. (1988). *Instructional manual gp tabletop centrifuge*. Palo Alto: Spinco Division of Beckman Instruments, Inc.

Bernal, A., Cardenoso, R., Fabrellas, C., Matia, L., & Salvatella, N. (1999). An aesthetic quality index for Barcelona's water supply. *Water Science and Technology, 40*(6), 23-29.

Bilotta, G. S., Bilotta, G. S., & Brazier, R. E. (2008). Understanding the influence of suspended solids on water quality and aquatic biota. *Water Research, 42*(12), 2849–2861. doi: 10.1016/j.watres.2008.03.018

Brasington, J., & Richards, K. (2000). Turbidity and suspended sediment dynamics in small catchments in the Nepal Middle Hills. *Hydrological Processes, 14*(14), 2559-2574. doi: 10. 1002/1099-1085(20001015)14:14<2559::AID-HYP114>3.0.CO;2-E

Brookes, J. D., Hipsey, M. R., Burch, M. D., Regel, R. H., Linden, L. G., Ferguson, C. M., et al. (2005). Relative value of surrogate indicators for detecting pathogens in lakes and reservoirs. *Environmental Science & Technology, 39*(22), 8614-8621. doi: 10.1021/es050821+

Coulter, B. (2007). *Instructions for using the gh-3.8 swinging bucket rotor* (p. 41). Fullerton: Beckman Coulter, Inc.

Davies-Colley, R. J., & Smith, D. G. (2001). Turbidity suspended sediment, and water clarity: A review. *Journal of the American Water Resources Association, 37*. doi: 10.1111/j.1752-1688.2001.tb03624.x

Effler, S. W., Johnson, D. L., Jiao, J. F., & Perkins, M. (1992). Optical impacts and sources of suspended solids in Onondaga Creek, U.S.A. *JAWRA Journal of the American Water Resources Association, 28*, 251–262. doi: 10.1111/j.1752-1688.1992.tb03991.x

Foster, G., Young, R., & Neibling, W. (1985). Sediment composition for nonpoint source pollution analyses. *Transactions of the ASAE-American Society of Agricultural Engineers (USA)*.

Gao, P., Pasternack, G., Bali, K., & Wallender, W. (2008). Estimating suspended sediment concentration using turbidity in an irrigation-dominated southeastern california watershed. *Journal of Irrigation and Drainage Engineering, 134*(2), 250–259. doi: 10.1061/(ASCE)0733-9437(2008)134:2(250)

Gee, G. W., & Bauder, J. W. (1986). Particle-size analysis. In A. Klute, ed., *Methods of soil analysis: Part 1—Physical and mineralogical methods* (pp. 383–411, SSSA Book Series): Soil Science Society of America, American Society of Agronomy.

Gerlach, R. W., & Nocerino, J. M. (2003). *Guidance for obtaining*

representative laboratory analytical subsamples from particulate laboratory samples: US Environmental Protection Agency, Office of Research and Development, National Exposure Research Laboratory, Environmental Sciences Division.

Gippel, C. J. (1995). Potential of turbidity monitoring for measuring the transport of suspended solids in streams. *Hydrological Processes, 9*(1), 83-97. doi: 10.1002/hyp. 3360090108

Hach, C. (2006). *Hydrolab DS5X, DS5, and MS5 Water Quality Multiprobles, User Manual* (3rd ed., p. 74). Ludwigstrasse 16, Germany: OTT Hydromet GmbH.

Harp, S. L., Barfield, B. J., Hayes, J. C., Yeri, S., & Chalavadi, M. (2008). *SEDPRO modeling of BMP effectiveness at construction sites*. Paper presented at the World Environmental and Water Resources Congress 2008: Ahupua'a, May 12, 2008–May 16, 2008, Honolulu, HI.

Hathaway, J. C. (1956). Procedure for clay mineral analysis used in the sedimentary petrology laboratory of the US Geological Survey. *Clay Minerals Bulletin, 3*, 8–13.

Hazelton, P. D., & Grossman, G. D. (2009). The effects of turbidity and an invasive species on foraging success of rosyside dace (*Clinostomus funduloides*). *Freshwater Biology, 54*(9), 1977–1989. doi: 10.1111/j.1365-2427.2009.02248.x

Henley, W., Patterson, M., Neves, R., & Lemly, A. D. (2000). Effects of sedimentation and turbidity on lotic food webs: A concise review for natural resource managers. *Reviews in Fisheries Science, 8*(2), 125–139.

Holliday, C., Rasmussen, T. C., & Miller, W. P. (2003). Establishing the relationship between turbidity and total suspended sediment concentration. In *Proceedings of the 2003 Georgia Water Resources Conference,* (pp. 23–24): The University of Georgia, Institute of Ecology, Athens, Georgia.

Holstrom, T. A., & Hawkins, R. H. (1980). Particle size distribution effects on turbidity. In *Symposium on Watershed Management, Boise, Idaho, 1980* (pp. 283–297). New York: Committee on Watershed Management of the Irrigation and Drainage Division, American Society of Civil Engineers.

Hoomehr, S., & Schwartz, J. S. (2012). Evaluating SEDCAD model performance on reclaimed coal mine lands in East Tennessee. *Journal of Irrigation and Drainage Engineering, 139*(3), 261–266.

Johnson, C., Flowers, A., Noriea, N., Zimmerman, A., Bowers, J., DePaola, A., et al. (2010). Relationships between environmental factors and pathogenic vibrios in the Northern Gulf of Mexico. *Applied and Environmental Microbiology, 76*(21), 7076–7084. doi: 10.1128/AEM.00697-10

Jones, A. S., Stevens, D. K., Horsburgh, J. S., & Mesner, N. O. (2011). Surrogate measures for providing high frequency estimates of total suspended solids and total phosphorus concentrations. *JAWRA Journal of the American Water Resources Association, 47*, 239-253. doi: 10.1111/j.1752- 1688.2010.00505.

Kim, J., & Furumai, H. (2013). Improved calibration of a rainfall-pollutant-runoff model using turbidity and electrical conductivity as surrogate parameters for total nitrogen. *Water and Environment Journal, 27*(1), 79-85. doi: 10.1111/j.1747- 6593.2012.00328.x

Kirk, J. O. (1985). Effects of suspensoids (turbidity) on penetration of solar radiation in aquatic ecosystems. *Hydrobiologia, 125*(1), 195–208. doi: 10.1007/BF00045935

Kirk, K. L. (1991). Suspended clay reduces Daphnia feeding rate. *Freshwater Biology, 25*(2), 357–365. doi: 10.1111/j.1365-2427.1991.tb00498.x

LeChevallier, M. W., & Norton, W. D. (1992). Examining relationships between particle counts and Giardia, Cryptosporidium, and turbidity. *Journal (American Water Works Association),* 54-60.

Lewis, J. (1996). Turbidity-controlled suspended sediment sampling for runoff-event load estimation. *Water Resources Research, 32*(7), 2299–2310. doi: 10.1029/96wr00991

Line, D., Hall, K., & Blackwell, J. (2013). Estimating suspended solids from turbidity in the Robeson Creek, NC watershed. *JAWRA Journal of the American Water Resources Association, 49*(6), 1412–1420.

Lloyd, D. S. (1987). Turbidity as a water quality standard for salmonid habitats in Alaska. *North American Journal of Fisheries Management, 7*(1), 34–45.

Marttila, H., & Kløve, B. (2012). Use of turbidity measurements to estimate suspended solids and nutrient loads from peatland forestry drainage. *Journal of Irrigation and Drainage Engineering, 138*(12), 1088–1096. doi: 10.1061/(ASCE)IR. 1943-4774.0000509

Microsoft. (2010). Microsoft Excel (Vol. Service Pack 1): Microsoft Corporation.

Minella, J. P., Merten, G. H., Reichert, J. M., & Clarke, R. T. (2008). Estimating suspended sediment concentrations from turbidity measurements and the calibration problem. *Hydrological Processes, 22*(12), 1819–1830.

Minitab. (2010). *Minitab 16 Statistical Software*. State College, PA: Minitab, Inc.

Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I—A discussion of principles. *Journal of Hydrology, 10*(3), 282-290. doi: 10.1016/0022-1694(70)90255-6

NCSS. (2000). Kamie series. National Cooperative Soil Survey, USDA Natural Resources Conservation Service, U.S.A. https://soilseries.sc.egov.usda.gov/OSD_Docs/K/KAMIE.html (Accessed July 4, 2015)

NCSS. (2004a). Port series. National Cooperative Soil Survey, USDA Natural Resources Conservation Service, U.S.A. https://soilseries.sc.egov.usda.gov/OSD_Docs/P/PORT.html (Accessed July 4, 2015)

NCSS. (2004b). Norge series. National Cooperative Soil Survey, USDA Natural Resources Conservation Service, U.S.A. https://soilseries.sc.egov.usda.gov/OSD_Docs/N/NORGE.html (Accessed July 4, 2015)

NCSS. (2007). Cecil series. National Cooperative Soil Survey, USDA Natural Resources Conservation Service, U.S.A. https://soilseries.sc.egov.usda.gov/OSD_Docs/C/CECIL.html (Accessed July 4, 2015)

NCSS. (2008). Pacolet series. National Cooperative Soil Survey, USDA Natural Resources Conservation Service, U.S.A. https://soilseries.sc.egov.usda.gov/OSD_Docs/P/PACOLET.html (Accessed July 4, 2015)

NCSS. (2014). Stephenville series. National Cooperative Soil Survey, USDA Natural Resources Conservation Service, U.S.A. https://soilseries.sc.egov.usda.gov/OSD_Docs/S/STEPHENVILLE.html (Accessed July 4, 2015)

Packman, J.J., Comings, K. J., & Booth, D. B.(1999). Using turbidity to determine total suspended solids in urbanizing streams in the Puget Lowlands; in Confronting Uncertainty: Managing Change inWater Resources and the Environment, Canadian Water Resources Association annual meeting, Vancouver, BC, 27–29 October 1999, p. 158–165.

Parmelee, C. L., & Ellms, J. W. (1899). On rapid methods for the estimation of the weight of suspended matters in turbid waters. *Technology Quartery and Proceedings of Society of Arts, XII*(2), 20.

Patil, S. S. (2010). Turbidity modeling based on the concentration of total suspended solids for stormwater runoff from construction Sites. Master's thesis, Oklahoma State University.

Pavanelli, D., & Bigi, A. (2005). Indirect methods to estimate suspended sediment concentration: Reliability and relationship of turbidity and settleable solids. *Biosystems Engineering, 9*(1), 75–83. doi: 10.1016/j.biosystemseng.2004.09.001

Perkins, R., Hansen, B., Wilson, B., & Gulliver, J. (2014). Development and Evaluation of Effective Turbidity Monitoring Methods for Construction Projects, Bruce Wilson, Principal Investigator. In U.M. Departments of Bioproducts/Biosystems and Civil Engineering, ed., (pp. 158): Minnesota Department of Transportation.

Pflüger, Y., Rackham, A., & Larned, S. (2010). The aesthetic value of river flows: An assessment of flow preferences for large and small rivers. *Landscape and Urban Planning, 95*(1), 68–78.

Riley, S. (1998). The sediment concentration-turbidity relation: Its value in monitoring at Ranger Uranium Mine, Northern Territory, Australia. *CATENA, 32*, 1–14.

Rügner, H., Schwientek, M., Beckingham, B., Kuch, B., & Grathwohl, P. (2013). Turbidity as a proxy for total suspended solids (TSS) and particle facilitated pollutant transport in catchments. *Environmental Earth Sciences, 69*(2), 373–380. doi: 10.1007/s12665-013-2307-1

Rügner, H., Schwientek, M., Egner, M., & Grathwohl, P. (2014). Monitoring of event-based mobilization of hydrophobic pollutants in rivers: Calibration of turbidity as a proxy for particle facilitated transport in field and laboratory. *Science of the Total Environment, 490*, 191–198.

Ruzycki, E., Axler, R., Henneck, J., Will, N., & Host, G. (2011). Estimating mercury concentrations and loads from four western Lake Superior watersheds using continuous in-stream turbidity monitoring. *Aquatic Ecosystem Health & Management, 14*(4), 422–432.

Ruzycki, E. M., Axler, R. P., Host, G. E., Henneck, J. R., & Will, N. R. (2014). Estimating sediment and nutrient loads in four Western Lake Superior streams. *JAWRA Journal of the American Water Resources Association, 50*(5), 1138–1154. doi: 10.1111/jawr.12175

Slaets, J. I., Schmitter, P., Hilger, T., Lamers, M., Piepho, H.-P., Vien, T. D., et al. (2014). A turbidity-based method to continuously monitor sediment, carbon and nitrogen flows in mountainous watersheds. *Journal of Hydrology, 513*, 45–57.

Smith, D. G., Croker, G. F., & McFarlane, K. (1995). Human perception of water appearance: 1. Clarity and colour for bathing and aesthetics. *New Zealand Journal of Marine and Freshwater Research, 29*(1), 29–43.

Soil Survey Division Staff. (1993). Soil survey manual. Soil Conservation Service. U.S. Department of Agriculture Handbook 18.

Soil Survey Staff. (2011). Natural Resources Conservation Service, United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database. http://sdmdataaccess.nrcs.usda.gov/ (Accessed October 10, 2011)

Sun, H., Cornish, P. S., & Daniell, T. M. (2001). Turbidity-based erosion estimation in a catchment in South Australia. *Journal of Hydrology, 253*(1–4), 227–238. doi: 10.1016/S0022-1694(01)00475-9

Teixeira, E. C., & Caliari, P. C. (2005). Estimation of the concentration of suspended solids in rivers from turbidity measurement: Error assessment. *Sediment Budgets, 1*, 151–160.

USEPA. (1999). Guidance manual for compliance with the interim enhanced surface water treatment rule: Turbidity provisions. United States Environmental Protection Agency.

USEPA. (2009). Environmental Impact and Benefits Assessment for Final Effluent Guidelines and Standards for the Construction and Development Category. U.S. Environmental Protection Agency Office of Water (4303T).

USEPA. (2014). Effluent Limitations Guidelines and Standards for the Construction and Development Point Source Category, Final Rule. In U.S. E. P. Agency, *EPA-HQ-OW-2010-0884; FRL-9906-51-OW; RIN 2040-AF44* (Vol. 40 CFR Part 450: , pp. 6): Federal Registar.

Warner, R., & Sturm, T. (2002). Turbidity as a surrogate to estimate the effluent suspended sediment concentration of sediment controls at a construction site in the southeastern United States. In *Proceedings of the Federal Interagency workshop on Turbidity and Other Surrogates. Reno NV April, 2002*.

Warner, R. C., Schwab, P., & Marshall, D. (1998). SEDCAD 4 for Windows 95/98 & NT, Design Manual and User's Guide. Civil Software Design, Ames, IA.

Wass, P. D., Marks, S.D., Finch, J.W., Leeks, G. J. L.,Wass, P. D., Marks, S. D., Finch, J. W., Leeks, G. J. L., Wass, P. D., Marks, S. D., Finch, J. W., Leeks, G. J. L., & Ingram, J. K. (1997). Monitoring and preliminary interpretation of in-river turbidity and remote sensed imagery for suspended sediment transport studies in the Humber catchment. *Science of the Total Environment, 194–195*(0), 263–283. doi: 10.1016/ S0048-9697(96)05370-3

Williamson, T. N., & Crawford, C. G. (2011). Estimation of suspended-sediment concentration from total suspended solids and turbidity data for Kentucky, 1978–1995. *JAWRA Journal of the American Water Resources Association, 47*(4), 739–749.

Zabaleta, A., Martínez, M., Uriarte, J. A., & Antigüedad, I. (2007). Factors controlling suspended sediment yield during runoff events in small headwater catchments of the Basque Country. *CATENA, 71*(1), 179–190. doi: 10. 1016/j.catena.2006.06.007