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IMPROVED SOIL MIXING AND DELIVERY SYSTEM FOR A STORM RUNOFF SIMULATOR

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ABSTRACT. *An earlier version of a storm runoff simulator to test conservation buffers reproduced target hydrographs and sedigraphs using uniform, fine sand; however, it was unable to uniformly mix and deliver native sediment. The objectives of this work reported were to create a method to process native agricultural sediment, mix a uniform sediment slurry at a target concentration, and create a control system that will deliver the slurry in varying flow rates corresponding to a target sedigraph. Eroded silty clay (14% sand) was scraped, dried, and processed with a hammer mill. A sand (93% sand) and loam (44% sand) were dried and screened for organic debris and large clods. Each soil type was mixed by an axial flow impeller in an 1890-L cone-bottom tank. Recirculation through a trash pump was used to further break down aggregates and maintain a uniform sediment concentration in the tank. A V-Port ball valve under pressurized flow was used to achieve outflow control. The sediment mixing system was capable of producing concentrations within 3.3% of the target concentration with a maximum test concentration of 0.294 kg L^{-1} with the silty clay soil. Simulated hydrographs had a Nash Sutcliffe Efficiency of 0.998, a Root Mean Square Error of 0.06 L s^{-1}, and a peak flow rate within 1% of the target flow. Simulated sedigraphs with silty clay had similar performance. Neither the sandy soil, nor the loam, were successfully delivered through the system to match target sedigraphs. The sand could not be uniformly mixed in the tank, but the loam was uniformly mixed to the target concentration.*

Keywords. *Hydrograph simulator, Runoff, Sediment, Erosion, Conservation buffers.*

Agricultural runoff containing pollutants such as sediment, nutrients, and pesticides has been the target of multiple research studies. Such investigations have targeted conservation practices and their ability to reduce the non-point source pollutant load into surface water. Conservation buffer strips have been shown to be effective at removing pollutants; however, the degree of their effectiveness in the field, especially during larger precipitation events, is relatively unknown. A hydrograph simulator was designed to create a more accurate representation of a natural runoff event than many of the previous smaller constant flow simulators developed to date. Such a device can be used to evaluate in-field efficacy of conservation buffers and other structures. The design proposed for the sediment mixing system requires a method to mix native sediment to a target concentration based on previously determined storm criteria (Franti et al., 2007a).

Rainfall and runoff simulators are advantageous for conducting replicated research because they are more rapid, efficient, and adaptable than natural rainfall events (Meyer, 1994). Natural storm events produce more realistic runoff scenarios than simulators, with a much larger runoff area to plot area ratio; however, the unpredictability of weather events makes data collection troublesome and replication is difficult. Rainfall simulators have been limited to relatively small study plots. Constant delivery rainfall simulators have been used with larger plots; however they are not representative of a natural runoff hydrograph. Runoff simulators have been used generally with constant flow rates (Mickelson and Baker, 1993; Misra et al., 1996; Schmitt et al., 1999) which are not representative of a natural runoff hydrograph (Sutko, 2007). Runoff simulations have been conducted using variable flow rates such as by Van Dijk et al. (1996) who used a valve set to a fixed position to achieve a variable flow rate from the reduced pressure head as a supply tank drained. Another method used by Dabney et al. (1993) involved manually adjusting the outflow rate from a water source in a step-wise fashion to produce a simulated hydrograph. Finally, Arora et al. (2003) conducted a runoff simulation by adjusting pumped flow rates (increasing and then deceasing) to create a more natural hydrograph.

A detailed literature review examining buffer strip effectiveness, testing, and modeling was reported by Franti et al. (2007a) and Sutko et al. (2008). Previous work to evaluate the effectiveness of vegetative filter strips has been lacking for one or more of the three following situations: (1) the ratio of the contributing up-slope area to the buffer area (BAR) was much smaller than the Natural Resources Conservation Service (NRCS) maximum design standard of 70:1, and often less than 5:1; (2) the perpendicular distance from the stream, the buffer width, often did not meet the minimum NRCS design standard of 6.1 m; and/or (3) the study used a constant flow rate of water, sediment and/or added nutrients and pesticides (Franti et al., 2007b). An exception to these three shortcomings was a study conducted

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by Arora et al. (2003), in which simulated runoff containing sediment, nutrients, and pesticides was applied at variable flow rates at 15:1 and 30:1 BARs on a 20.1-m wide filter strip.

In addition to the three issues stated above, Sutko et al. (2008) reported that most simulations did not represent extreme rainfall conditions. Many authors indicated that mean sediment concentration can be greater than 0.1 kg L^{-1} (Robinson et al., 1996; Le Bissonnais et al., 1998; Cerdan et al., 2002; Wilson et al., 2004). It can then be reasonably inferred from these studies that the maximum concentration is greater than 0.1 kg L^{-1}. Storm simulators that have been created previously have used different methods in order to create and maintain a uniform concentration of water and contaminates. Some of the different mixing processes include: recirculation pumps (Garcia and Parker, 1989; Mickelson and Baker, 1993; Van Dijk et al., 1996; Schmitt et al., 1999; Arora et al., 2003;); air jets (Gharabaghi et al., 2001; Abu-Zreig et al., 2004); water jets (Lee et al., 2008); agitators (Tollner et al., 1976; Deletic, 1999; Sutko et al., 2008); and dry hopper feeds (Hook, 2003). The sediment loads from the simulators described ranged from 0.00065 to 0.1 kg L^{-1}, with the largest sediment load per plot at 50 kg (Hook, 2003). None of these simulators were able to create sediment discharge rates representing a natural runoff hydrograph.

Storm Runoff Simulator Development

The goal of this project was to create a storm runoff simulator that could be used for in-field testing of vegetative buffer strips and other conservation buffers. The focus of subsequent use of the simulator will be to determine contaminant removal efficiencies of conservation practices. The first three phases of this project included: 1) a feasibility study and development of project size constraints (Franti et al., 2007a); 2) development of a hydrograph creation system (Franti et al., 2007b); and 3) development of an artificial sediment mixing and delivery system (Sutko et al., 2008). The portion of the project reported here extends the previous work to create a native sediment mixing and delivery system (Alms, 2009). The objectives were to: 1) create a methodology to process field soil into eroded sized particles; 2) uniformly mix these particles as a sediment slurry to a predetermined target concentration; and, 3) create and test a flow control system that is capable of performing with abrasive sediment slurry, and be environmentally secure.

Simulator Control System Design

A previous study by Sutko (2007) reported on a mixing and metering system for fine silica sand, using gravity flow. When native soil (silty clay) was used in this system the flow meter failed because clay particles clogged the meter's rotary mechanism. The design for the current control system avoided this problem by using a magnetic meter with no moving parts.

Agricultural soil consists of many different sizes and densities of particles, so the system required professional design and sizing. The sediment mixing system consists of a conical bottom 1890-L tank, a portable mixer professionally sized by Brawn™ Mixer Inc., and a 4.85-kW (6.5-hp) trash pump to recirculate the slurry from the bottom to the top of the tank. The control system was designed using a magnetic flow meter and a V-port control valve to withstand the abrasive sediment slurry, and to add more accuracy to the flow control. Two Y-strainers were included to act as a refining process to remove any large debris, such as large pebbles or organic matter. The design of the sediment mixing system is shown as a schematic drawing (fig. 1). This one-tank system is considered a half-scale, prototype mixing system which will be duplicated as a two-tank system to reach the total required sediment mass for the maximum design storm (Franti et al., 2007a). The system is based on pressurized flow provided by the mixing pumps.

The mixing tank was designed such that the pump recirculation rate would not interfere with the impeller mixing action and not reduce the effective mixing ability of the tank, according to the manufacturer's engineering specifications. A 7.6-cm, 4.85-kW (6.5-hp) trash pump made by Hypro™ Pumps was used that can handle solids up to 2.86-cm diameter. The pumping head curve (PHC) as reported by the manufacturer was compared to the system head curve (SHC) calculated using the Darcy-Weisbach equation to calculate losses. If this pump was operated at the ideal point of approximately 14 L s^{-1} it would recycle the maximum volume of the slurry every 1.9 min. The recycle time for the impeller is approximately 0.21 min, which is determined by dividing the slurry volume by the calculated pumping flow rate of the impeller. Given that the impeller will recycle slurry 9 times faster than the trash pump, there should be little interference between the trash pump and the impeller's mixing motion (Brawn Mixer, Inc., 2003). However, no additional analysis was conducted to see if the recirculation rate was over designed or just adequate.

The control system included a McCrometer full bore magnetic flow meter (Hemet, Calif.), an A-T Controls V-port control valve (Cincinnati, Ohio), a National Instruments Compact Data Acquisition System (Austin, Tex.), and a control program written in National Instruments Lab-VIEW™ 8.2 (Austin, Tex.). The control system created a durable, environmentally resistant device, with accuracy and controllability.

A V-port control valve was determined to be the most suitable mainly because the passageway through the control valve, or valve trim, is almost always reduced to allow the full range of the valve to be used to control the flow. Full port valves provide poor flow controllability because they only use a small portion of the valve range (Skousen, 1998). Also, the V-port valve position is calibrated to a defined milli-volt signal; that is, sending a known signal will open the valve to the same position each time that signal is sent.

The magnetic flow meter was included in the design for research and calibration. Once the system is fully designed, tested and calibrated, the flow rate can be determined based upon the position of the V-port valve, pressure differential across the valve, and the measured specific gravity of the fluid.

The cDAQ™-9172 data logger (National Instruments, Austin, Tex.) offered a sampling rate of 500 kS s^{-1}, sufficient signal measurement resolution, and frequency measuring hardware that can determine the instantaneous flow rate in the magnetic meter, as opposed to a time averaged pulse count. The cDAQ™ was configured with a NI 9203 analog

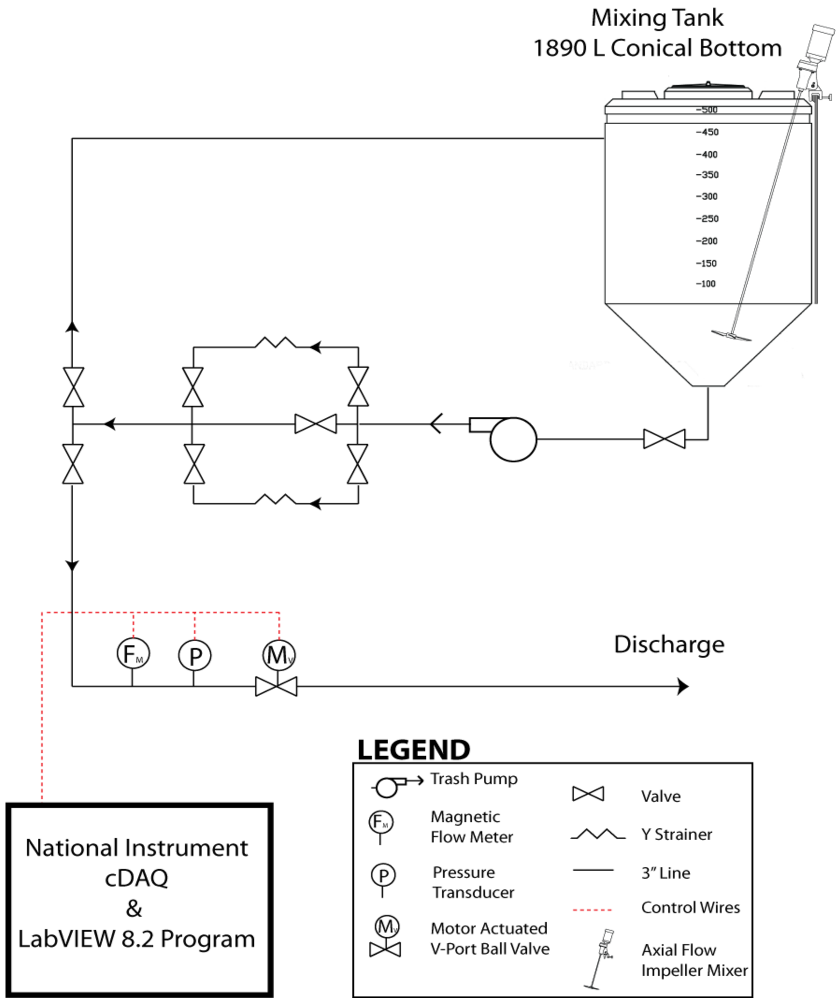

Figure 1. Sediment mixing system schematic with tank gradations in gallons.

current input module, a NI 9201 analog current output module, a NI 9201 analog voltage input module, and a NI 9411 differential digital input module. The cDAQ™ used a 24-V power supply to power the analog output module, and a 5-V supply on the digital input card and the pressure transducer.

The LabVIEW™ control program reads data from an Excel or text file, and generates a hydrograph shaped outflow by opening and closing the control valve. The data inputs for this program could be created from another hydraulic modeling program that simulates unique hydrograph and sedigraph flow rates for the specific plot being tested. The generated hydrograph (target and actual) is displayed on a real-time X-Y Chart on the front panel of the program. Additionally, the program calculates the concentration of the sediment slurry from a pre-measured specific gravity adjusted based on a measured slurry temperature. This concentration is then multiplied by the magnetic meter flow rate and the sediment rate data is added to the X-Y chart on the front panel. These real-time data, and many other intermediate values, allow the operator to ensure that the system is operating correctly, and make necessary adjustments to prevent any data loss.

A basic component list and cost estimate for the prototype sediment mixing system was developed (table 1). Miscellaneous costs for piping, fixtures, etc. were included (in addition to those listed), and operating costs (electrical, water, gas) were not included. This cost estimate provides a guideline for the basic mechanical, piping, and controls, excluding a computer used for data acquisition and control. Finally, the cost estimate does not include a trailer and scaffolding that was used to secure the equipment in the field.

Experimental Methods

Parameters of the target simulated storm were based on data developed by Sutko et al., (2008). This simulated storm was created using the SCS Curve Number Method, the Modified Universal Soil Loss Equation (MUSLE), and a distribution technique to create simulated hydrographs and sedigraphs (Sutko et al., 2008). The design storm requires the full-scale runoff simulator to have a maximum water volume of 7580 L and a peak water flow rate of 7.3 L s^{-1}. A maximum sediment load of 882 kg and a peak sediment discharge rate of 1.15 kg s^{-1} are also needed.

The Wymore silty clay (14% sand, 58% silt, 28% clay, 4.1% O.M.) used in these experiments was eroded soil deposited at a terrace riser inlet at the University of Nebraska Rogers Memorial Farm, 16 kilometers east of Lincoln, Nebraska. The sand soil (93% sand, 4.5% silt, 2.5% clay, 0.2% O.M.) and Olmitz loam (66% sand; 25% silt; 9% clay, 2.0% O.M.) were noneroded soil obtained from crop rows at

Table 1. Component cost summary with prices based on 2008 quotes.

Components	Price ($)	Qty.	Total Price ($)	Manufacturer, City, State
Flow Measurement				
McCrometer ultra-mag flow full bore magnetic meter	2,805	1	2,805	McCrometer, Inc., Hemet, Calif.
Flow Control				
AT controls V-port ball valve and actuator	3,200	1	3,200	AT Controls, Cincinnati, Ohio
Omega 15 psig voltage press. trans. w/ calib.	350	1	350	Omega Engineering, Inc., Stamford, Conn.
Mating connector for PX329	26	1	26	Omega Engineering, Inc., Stamford, Conn.
Electronics				
CDAQ-9172 8-slot USB 2.0 chassis	1,049	1	1,049	National Instruments, Inc., Austin, Tex.
NI 9411 6 channel DI module	1,435	one set of five	1,435	National Instruments, Inc., Austin, Tex.
NI 9935 15pin D-sub connector				
NI 9203 8 channel current input module				
NI 9265 4 channel current output module				
NI 9201 8 channel analog input module				
7.6-cm Pipe and Fittings				
Line strainer with 4-mesh screen	183	2	366	Kelly Supply, Lincoln, Nebr.
Poly pipe tee	23.45	7	164	Kelly Supply, Lincoln, Nebr.
Standard port ball valve F-NPT/F-NPT	48.13	4	192	Kelly Supply, Lincoln, Nebr.
Standard port ball valve F-NPT/F-NPT	50.45	4	202	Kelly Supply, Lincoln, Nebr.
Misc. fitting, valves, pipes	465	–	465	Kelly Supply, Lincoln, Nebr.
Other				
6.5-HP 3-in. BPT aluminum trash pump	400	1	400	Surplus Stores, Lincoln, Nebr.
500-gal 45- cone bottom tank	452	1	452	Ace Roto-Mold, Hospers, Iowa
Stand for 8879 cone tank, with modifications	436	1	436	Ace Roto-Mold, Hospers, Iowa
Brawn Mixer MG50-350 1/2-HP 1.9-cm × 122-cm SS shaft w/ 33-cm AF3 impeller	1,870	1	1,870	Brawn Mixer, Inc., Holland, Mich.
66- × 3/4-in. shaft	175	1	175	Brawn Mixer, Inc., Holland, Mich.
		Total:	$13,587	

the University of Nebraska Agricultural Research and Development Center farms, 64 km north of Lincoln, Nebraska. All soils were analyzed for soil texture and organic matter content (O.M.) by Ward Laboratories in Kearney, Nebraska.

The sand and loam soils were hand shoveled into buckets, transported to the Rogers Memorial Farm and stored out of sun and rain. Screening and hand removal of large clods and residue was the only processing of the sand and loam. The silty clay soil was air dried below approximately 18% moisture content on a dry mass basis. It was loaded into a sloped bottom hopper that was mounted over a Lindig hammer mill. The soil that passed through the hammer mill was less than the 2.54 cm in diameter maximum particle size capacity of the recirculation pumps.

A calcium carbide gas moisture tester (Speedy Moisture Tester) was used for estimating initial soil moisture content. Before soil was prepared for loading into the mixing tank one or two samples were collected from the processed stockpile, approximately 15 to 25 cm below the surface of the pile, and soil moisture content readings were taken with the Speedy Moisture Tester (Saskatchewan Highways and Transportation, 1993). As a control, a soil sample was collected in a standard soil sample can and dried in an oven at 105°C for 48 h as a reference for the Speedy Moisture Tester accuracy. The advantage to using the Speedy Moisture Tester is that it is easy to use, the result is achieved quickly, the accuracy was within about ±1-2% of the oven-dried moisture content, and it does not need to be calibrated for different soil types. The Speedy Moisture Tester tended to give a lower first moisture content reading, compared to oven dry values, early in the day when the ambient air temperature was 10°C to 15°C. In this case a second sample was tested, and judgment used to select which value to use.

Sediment Mixing

Once a soil was processed, 18.9-L (5-gal) buckets were filled and weighed. Each bucket held between 18 and 22 kg of soil depending on the soil moisture content. The buckets were separated into groups of five, and a small sample from each bucket was collected and placed in a sample can to be analyzed for final moisture content.

The soil was added to 1420 L of water in the mixing tank. Water volume was measured with a propeller flow meter on a garden hose that was used to fill the tank. With the mixer and the pump turned on and flow bypassing the Y-strainers, the soil was added to the tank. For the silty clay and loam, groups of five buckets were added to the tank at the rate of approximately one bucket every minute. After 5 min of adding soil, 10 min elapsed to allow the soil to mix and breakdown. This process continued until the appropriate amount of soil was added. After the last mixing period the valves were opened to transfer the flow through the Y-strainers. The Y-strainers, with a 4750-µm mesh size (No. 4 U.S. mesh size), were included to remove larger particles and organics. Twigs and organics were the primary material removed by the strainers.

In the case of the sand soil (93% sand) buckets were added in groups of two buckets at a time. The recirculating pump was monitored to the point it was judged it could no longer operate under the sand load it was pumping and failure was pending. At this point no more sand was added to the tank, thus establishing the maximum mixed concentration.

Testing Sediment Concentration

After the straining period, two 1-L slurry samples were taken from the top of the water column from the circulating slurry. The outlet was opened and the slurry drained from the tank while 1-L slurry samples were grabbed from the outflow for approximately every 114 L. The time that each sample was taken was recorded and an approximate discharge rate was determined. Once the slurry reached the ~190-L level in the tank, the surface of the slurry fell below the bottom of the mixing impeller. At this point, because of the high pump suction head, a vortex began to form in the cone of the tank, dramatically reducing the flow rate out of the system. Samples were taken until the slurry level reached the 38-L mark on the tank. Samples were oven dried at 105°C for 5 days. The sampled sediment concentrations were then compared with the target concentration to determine uniformity of mixing and outflow concentration.

Generating Hydrographs and Sedigraphs

The flow control system developed by Franti et al. (2007b) was tested with the silty clay soil slurry without success because of failure of the paddle-wheel flow meter, and sediment clogging at the control valve. As a result, a new control system was designed as previously described. The first step was to calibrate the magnetic flow meter and the control valve with water, and then compare the results to readings using sediment slurry. A 1140-L weigh tank was used with a 4540-kg capacity Weigh-Tronix scale as a reference for flow rate. The weight changes were logged into a LabVIEW™ program through a serial connection from the scale weight indicator. Calibration data was recorded for valve percent openings of 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%. For each percent opening an average pressure and flow rate were logged. When the sediment slurry was introduced a hydrometer was used to measure the specific gravity. Using those flow rates, pressures, and the specific gravity values, a valve coefficient value (C_v) was determined for each percentage opening of the valve (eq. 1). With that information a hydrograph can be created by varying the valve opening with time.

$$C_v = \frac{Q}{N_1}\sqrt{\frac{S_G}{\Delta P}} \quad (1)$$

where Q is the flow rate, SG is the specific gravity of the fluid, ΔP is the pressure differential across the control valve, and N is a numerical constant based on the units used. For SI units Q and P should be in $m^3\ h^{-1}$ and kPa, and for English units these variables should be in gpm and psi, respectively. The value for N_1 in SI units is $8.65 \times 10^{-2}\ m^3\ kPa^{-0.5}\ h^{-1}$ and in English units is 1.0 gpm $psi^{-0.5}$.

Water was metered from the tank to match a target hydrograph using the control valve and measuring equipment. Magnetic meter, control valve, and weigh tank readings, and target flow rates were all logged in a spreadsheet in real time. Comparison of the measured outflow rates to the target hydrograph was performed using the Nash Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970) and the Root Mean Square Error (RMSE). The NSE ranges from minus infinity to one, with one being the best correlation. Physically it is the ratio of the mean square error to the variance in the observed data, subtracted from unity (Legates and McCabe, 1999). The RMSE has a perfect fit value of zero; however, the range depends on the units used in the calculations. The third comparison of results was the percent difference in the target and measured peak outflow rate. The importance of reaching the peak flow rate is in meeting the objective to deliver a specified peak sediment rate to a vegetative filter.

During preliminary field tests with sediment slurry, a valve hysteresis effect was observed, resulting in outflow rates greater than the target values when the valve was closing during the recession limb of the hydrograph. No matter how closely machined or expensive a valve is, it is reasonable to expect a slight degree of hysteresis when the valve changes direction of travel. Laboratory experiments were conducted to determine if the hysteresis varied at different percent valve openings. While slight variations were observed, experiments showed that the AT Controls valve has a hysteresis of approximately 5% of the full travel of the valve at all percent openings. To compensate for the hysteresis the control program was modified to add or subtract a constant to the desired input whenever the valve changes direction regardless of whether the change is from open to closed or closed to open. This correction essentially eliminated the hysteresis problem which further allows the system to produce single, as well as multi-peak, hydrographs.

Results

The silty clay soil was successfully mixed and metered through the control system at the desired concentration. Neither the loam nor the sand could be metered through the control valve successfully at a uniform concentration. For the silty clay soil the system reached a maximum concentration of 0.294 kg L^{-1}, which was within 3.3% of the target concentration. A greater concentration may have been possible, but was not attempted. For the sandy soil the maximum concentration reached was 0.13 kg L^{-1}, before imminent pump failure caused by the heavy sediment load through the pump. For the loam soil the target concentration was reached at 0.31 kg L^{-1} uniformly mixed in the tank. The hydrographs created with water only matched the target hydrograph very well, and had a mean NSE of 0.998, a RMSE of 0.06 L s^{-1}, and peak flow rates within 1% of the target rate.

The mixing tank system with the bypass recirculation line, conical bottom tank and trash pump before the discharge line, prevented soil from settling out in the tank. However, both the loam and sand settled in the pipe delivery system. At low flows, the scour velocity in the pipes could not be maintained with appreciable sand in the flow. The soil and water quantities used were for a prototype-scale, time-compressed hydrograph. A full-scale sediment mixing system using two mixing systems similar to the one created for this study, used in parallel, would be capable of producing a full-scale sedigraph for the selected design storm, with high accuracy, using silty clay soil.

Concentration Mixing Results

Grab samples from five runs with silty clay were taken at similar discharge rates, but different target sediment concentrations. The average discharge flow rates ranged from 4.6 to 5.5 L s^{-1}. The uniformity of the concentration for the five runs is represented by the standard deviations which were all less than 0.00127 kg L^{-1}. Specifically the standard deviations were 0.00109, 0.00117, 0.00082, 0.00059, and 0.00127 kg L^{-1} which corresponds to 0.81%, 0.65%, 0.39%, 0.23%, and 0.44% of the average discharge concentration for runs one through five, respectively (fig. 2).

The loam soil was uniformly mixed in the tank, with differences of 0 to -10% of the calculated and final target concentration. The sand could not be uniformly mixed in the tank. Concentrations were -25% to -50% of the calculated values, and the target concentration was never reached. The sand was only mixed to approximately 0.130 kg L^{-1}, well below the target of 0.30 kg L^{-1}.

Design Hydrograph and Sedigraph

With the cDAQ™ system and improved control program a smooth target hydrograph could be used as the input hydrograph (fig. 3). Four replications of the hydrograph using water only were created in the laboratory. In order to produce the complete compressed hydrograph, the weigh tank needed to be drained between eight and eleven minutes because it was full; therefore, a data gap exists at this time in the weigh tank flow rate (fig. 3). For this reason the comparison between the magnetic meter and the target flowrate is the best depiction of the input and measured hydrographs. The four replications had an average RMSE and NSE of 0.06 L s^{-1} and 0.998, respectively, and the average difference in measured to target peak flow for the four runs was -0.17%.

Three replications of the target sedigraph using silty clay were created in the field. In order to produce the complete hydrograph the slurry accumulating in the weigh tank was continuously recirculated to the mixing tank so there was no gap in the data (fig. 4). The measured flowrate (Mag Meter, fig. 4) for the three repetitions matched very closely to the target sedigraph, with descriptive statistics similar to the hydrograph output. The average statistics for the three replicates were a mean NSE of 0.995 a RMSE of 0.007 L s^{-1}, and peak flow rates within 2% of the target rate.

For both the sand and loam soil only one replicate was metered through the valve system. The sand soil clogged the outlet pipe for about 2 min until approximately 50% valve opening, then water and sand finally flowed out. High concentrations were predominant as slugs of sediment built up and were washed from the system (fig. 5). The loam soil also had generally greater outflow concentrations than the target value at valve openings less than 40%, but matched the

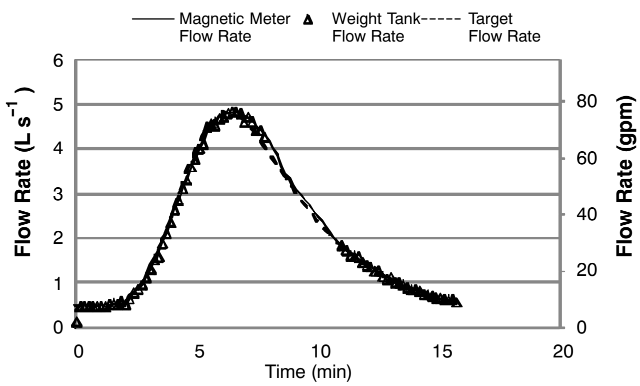

Figure 3. Hydrograph with NSE of 0.998 between magnetic meter measured flow rate and target flow rate.

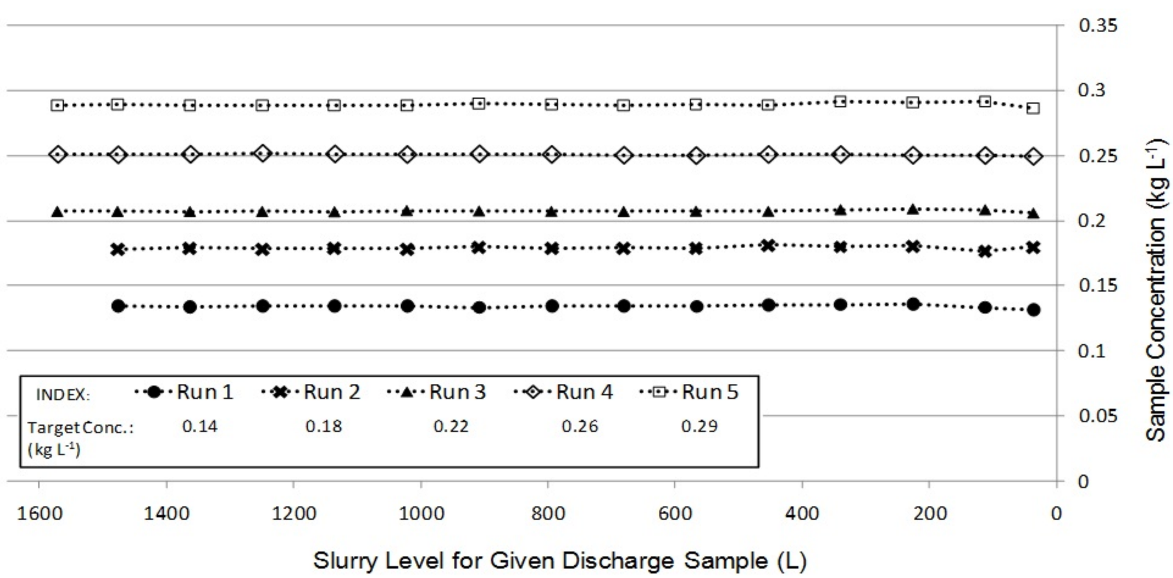

Figure 2. Concentration fluctuation as the mixing tank drains.

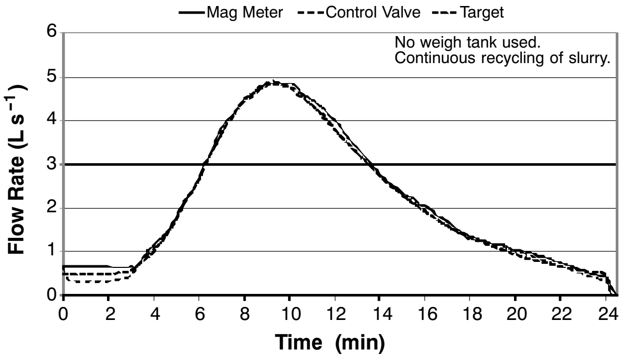

Figure 4. Slurry flow rate for silty clay sedigraph, replicate 3, including target, Magnetic meter reading (measured flow rate), and control valve setting flow rate. Replication 1 and 2 produced similar graphs.

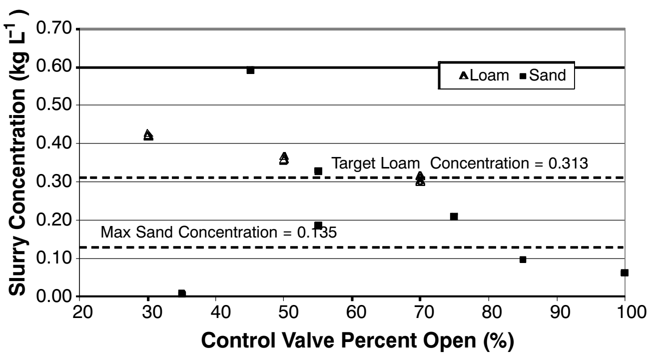

Figure 5. Soil slurry outflow concentration for loam and sand based on one replication.

target concentration above 50% opening (fig. 5). This improved accuracy at greater valve opening can be attributed to the uniform tank mixing of loam soil once a greater valve opening moved the settled sand more quickly through the piping system. However, if sand was present as a substantial component of the soil slurry it settled out too quickly in the pipeline, or was conveyed too slowly through the metering system to provide a uniform concentration in the outflow sedigraph.

Summary and Conclusions

This research project had three main objectives which included: 1) process and mix three agricultural soils into a soil slurry; 2) evaluate the uniformity of slurry concentration within the mixing tank and throughout the discharge system; and, 3) deliver a variable sediment flow rate to generate a hydrograph and sedigraph based on the design criteria set forth in the project description.

The eroded silty clay soil used was taken from the field, run through a hammer mill and weighed into 18.9-L buckets and effectively mixed to a uniform concentration in the mixing system. The sand and loam soil were screened, but not processed with the hammer mill. It was not possible to mix the sand soil (93% sand) to a uniform concentration in the mixing tank, or deliver it through the pipe system. With the 1890-L conical bottom tank, 0.373-kW (0.5-hp) impeller mixer, and 4.85-kW (6.5-hp) trash pump in a recirculation line, a uniform sediment concentration was achieved for both the silty clay and the loam, but the loam could not be delivered through the metering system at a uniform concentration.

For the silty clay approximately 96% of the soil was broken down finer than sand-sized particles in this process, which represented primary particles, not eroded soil particles. The maximum concentration reached was 0.294 kg L^{-1} which was within 3.3% of the target concentration. The outflow concentrations measured at five different target concentrations were uniform during tank drawdown, with a maximum standard deviation of 0.00127 kg L^{-1}.

The time compressed 5-yr, 2-h SCS design storm used in previous work was recreated, and replicated sedigraphs were successfully created with the control system using silty clay soil only. The control system included a McCrometer full bore magnetic flow meter, an A-T Controls V-port control valve, a National Instruments Compact Data Acquisition System, and a control program written in National Instruments LabVIEW™ 8.2. The control system created a durable, environmentally resistant device with accuracy and controllability.

The close fit Nash Sutcliffe Efficiency of 0.998, and the difference in peak flow of less than 1% for a target hydrograph (water), show that the system is capable of delivering a desired hydrograph. The close fit for three replicated silty clay sedigraphs (mean NSE = 0.988; mean RMSE = 0.06 L s^{-1}) indicates the system can reproduce a target output with soils that remain suspended during mixing and outflow. This mixing system and control program has the potential to be used in several different combinations and configurations in the future, primarily with soils consisting of silt and clay textures.

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