TRANSPORT CHARACTERISTICS OF TILE-DRAIN SEDIMENTS FROM AN AGRICULTURAL WATERSHED

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Abstract: The use of tile drains for subsurface drainage in agricultural watersheds has created concern for the delivery of sediment to receiving waters and potential undesirable effects on surface and subsurface water quality. In this study, transport characteristics of sediment from tile drains in an agricultural watershed of the Thames River, near Kintore, Ontario, Canada were tested in a 5 m diameter, rotating circular flume located at the National Water Research Institute in Burlington, Ontario. Tile drain sediments were collected and mixed with river water at different speeds in the flume to study transport processes such as deposition, erosion and flocculation as a function of bed shear stress. During deposition and erosion experiments, water samples were collected to determine changes in the concentrations of cations, anions and dissolved organic carbon. The results show that tile drain sediments have a tendency to flocculate when subjected to a range of shear stresses. The median diameter (D_{50}) of the floc size distribution reached a maximum value at a shear stress of 0.169 Nm^{-2} which can be considered an optimum shear stress for flocculation for this sediment. The critical shear stress at which all of the initially suspended sediment deposited to the flume bed was measured as 0.056 Nm^{-2}. The pH and cation concentrations remained relatively constant during erosion and deposition experiments. Anion concentrations were more variable, most likely due to the presence of bacteria which could have also played a role in the flocculation mechanism of tile drain sediment.

Key Words: Tile drains, cohesive sediment, flocculation, rotating flume

1. Introduction

Subsurface drainage is a common agricultural water management practice in areas with seasonally perched water tables or shallow groundwater. In southern Ontario, agricultural drainage activity began during the middle of the last century, but since 1960, it has increased both in extent and intensity (Kelly, 1975). The extent of agricultural drainage has created concern for its potential undesirable effects on surface and subsurface water quality. Tile drainage and agricultural runoff are sources of bacteria (Panti *et al.* 1984; Palmateer *et al.* 1993), contaminants (Kladviko *et al.* 1991; Mostaghimi *et al.* 1992; Richards and Baker, 1993) and suspended solids (Culley *et al.* 1983).

Tile drains can selectively transport fine-grained sediment from soils to receiving freshwater fluvial systems (Grass *et al.* 1979). However, there is a lack of information regarding both the delivery and transport characteristics of this material in agricultural watersheds (Stone and Droppo, 1994). Such information is required to model the source, transport and fate of cohesive sediment and associated contaminants for management purposes. In this paper, the transport characteristics of tile drain sediment collected from a southern Ontario agricultural watershed are studied in the laboratory using a rotating annular flume. Transport characteristics (erosion, deposition,

Water, Air and Soil Pollution **99**: 89-103, 1997.

flocculation) of the sediment are measured and related to water chemistry for a range of turbulent flow conditions.

2. Methods

2.1 STUDY AREA:

The study area is located in a headwater catchment of the Thames River, near Kintore Ontario. Silt-loam soils at this site have developed in silty alluvial deposits that overlie calcareous loam till. The study site has been drained by tile drains for over thirty years by a series of twelve tile drains that run perpendicular to the stream. Twelve soil pits were dug at the downslope edge of an experimental plot to sample sediment in the exposed tiles. The drains connect at a header before discharging into the stream. Approximately 5 kg of sediment was collected from tile drains for the flume experiments and additional samples of soils (directly above the tile drains), as well as river bottom sediment (above and below the tile drain outlet), were collected to determine sediment geochemistry and mineralogy. Approximately 100 m upstream from the tile drain outlet, 500 L of river water was collected for the flume experiments.

2.2 CHEMICAL ANALYSIS OF SEDIMENT AND WATER:

Concentrations of major elements (SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, K_2O, TiO_2, MnO, P_2O_5) and mineralogy of the sediment were determined using X-ray fluorescence (XRF) and X-ray Powder Diffraction (XRPD), respectively, at McMaster University, Hamilton, Ontario. Results are reported as percent dry weight. Accuracy of the samples was checked by running Canadian Reference Standards and comparing the stated reference values for major elements.

Water samples collected from the river, tile outlet and flume over a range of turbulent flow conditions for both the erosion and deposition experiments were analyzed for cations, anions and dissolved organic carbon (DOC). The cations including calcium (Ca), magnesium (Mg), sodium (Na), potassium (K) and silica (Si) were analyzed using a Thermo JarralAsh Inductively Coupled Spectrometer. The instrument was calibrated with commercially available EPA certified standards following EPA Contract Laboratory Protocol. The samples are filtered (0.45 μm) and acidified to a pH <2 with trace HCl. The anions including nitrate (NO_3^-), sulphate (SO_4^{2-}) and chloride (Cl^-) were analysed using a Dionex System 2000 ion chromatograph. Alkalinity was measured by titrating the sample to a pH 4.3 end point. The total alkalinity is reported as ppm HCO_3. Dissolved organic carbon (DOC) was analyzed using a Dohrmann DC 190 Carbon Analyzer. Cation and anion data were used to calculate ionic strength.

2.3 ROTATING FLUME EXPERIMENTS:

2.3.1 Description of the Flume:

The rotating, circular flume is 5.0 m in diameter, 0.30 m wide, 0.30 m deep and rests on a rotating platform 7.0 m in diameter. The flume assembly consists of a top cover, which fits inside the flume with close tolerance (~1.5 mm on either side). The height of the top cover can be adjusted so that it makes contact with the water surface inside the flume. By rotating the flume and the top cover in the opposite direction at different speeds, it is possible to generate nearly two-dimensional flow fields with different turbulent shear stresses and turbulence intensities. Complete details of the flume and its flow characteristics are found in Krishnappan (1993).

2.3.2 Instrumentation:

The flume is equipped with a Laser Doppler Anemometer (LDA) that operates in the back-scatter mode to measure the flow field. The Laser and optics are mounted on an optical bench, positioned on the rotating platform beside a glass window of the flume. The optical bench can be traversed both in the vertical and horizontal directions. In this configuration, the instrument measures the tangential and vertical velocity components from which the time average velocities and turbulent shear stress acting on the horizontal plane in the tangential direction can be extracted. Measurements made using this instrument were used to verify a 3-D numerical model of turbulent flows in rotating flume assemblies (Petersen and Krishnappan, 1994; Krishnappan *et al.* 1994).

The size distribution of suspended sediment in the flume is measured with a Malvern Particle Size Analyzer that operates on the Fraunhoffer diffraction principle (Weiner, 1984). The instrument is mounted in a cradle beneath the flume and operates in the continuous flow-through mode. The flow-through cell of the Malvern is connected to a sampling tube fitted through the bottom of the flume. The tube faces the flow and extends up to mid-depth at the centre of the flume. The sediment suspension is drawn continuously from the flume by gravity through the sample cell then returned to the flume. The sampling tube length to the cell is kept at a minimum to reduce changes in floc structure due to the flow field that exist within the tube. With this arrangement, the instrument is capable of measuring the in-situ size distribution of the sediment flocs in the flume. The flume is also fitted with sampling ports for drawing sediment water mixture for the purpose of determining the concentration of suspended sediment and for chemical analysis. The sediment concentration was determined by the filtration method (Environment Canada, 1988).

2.3.3 Experimental Procedure:

Two types of experiments were conducted in the flume. The first type dealt with deposition behavior while the second type examined erosion characteristics of the sediment. For the deposition tests, the sediment-water suspension was thoroughly mixed by first re-suspending any deposited sediment using a brush and then further breaking-up flocs with an electric blender. The depth of water inside the flume was adjusted to 12.0 cm. The top cover was then lowered until it penetrated the water surface by about 3 mm to ensure proper contact with the water in the flume. Trapped air was removed by rotating the top cover while the flume was kept stationary. To begin the deposition test, the flume and the top cover were rotated in opposite directions at their maximum speeds for twenty minutes to thoroughly mix the sediment and water and to further break up the flocs. During this high speed operation, sediment samples were collected for sediment concentration measurements every five minutes and the size distribution was determined every two minutes with the Malvern Particle Size Analyser. Water samples for chemical analysis were collected at the 10 minute mark. After 20 minutes, flume speeds were reduced to a particular bed shear stress and maintained for a period of about five hours.

Additional water samples were collected for chemical analysis at the 60 minute and 240 minute mark for each shear stress condition.

For the erosion experiment, the sediment-water mixture was left undisturbed for a period of 114 hours to allow the sediment to settle and age on the flume bed. The speeds of the flume and top cover were increased in steps so that the shear stress is applied as a stair-case function. At each step, the sediment concentration in the flume and size distribution of the eroded sediment were measured as a function of time. Water samples were also collected at each shear stress level for chemical analysis.

3 Results

3.1 DEPOSITION RESULTS:

3.1.1 Suspended sediment concentration:

The time variation of suspended sediment concentration during the deposition experiments are shown in Fig.1. For a particular shear stress, the sediment concentration decreases at a faster rate at the start of the experiment then gradually reaches a steady state value. The time to reach steady state value and the magnitude of the steady state concentration depends on the bed shear stress. The time to reach steady state decreases as shear stress increases and the magnitude of steady state concentration increases as bed shear stress increases. The bed shear stress values in these experiments range from 0.056 Nm^{-2} to 0.324 Nm^{-2} and sediment deposition occurred under all shear stress conditions examined. At the lowest shear stress, the sediment concentration drops from the initial 250 mgl^{-1} to about 30 mgl^{-1}. If the bed shear stress were slightly lower than this value, all of the initially suspended material would have deposited. Such a shear stress condition is termed the critical shear stress for deposition. At the maximum shear stress tested, the steady state concentration is about 150 mgl^{-1} which represents about 60% of the initially suspended material. Therefore, we see that deposition of sediment has occurred in all shear stress conditions tested.

3.1.2 Size distribution of suspended sediment flocs:

Changes in the median diameter (D_{50}) of the suspended sediment distributions plotted as a function of time are shown in Fig.2. From this figure, we could infer the flocculation behaviour of the sediment and its dependency on bed shear stress. When the bed shear stress is low (low turbulence level), the median diameter of the sediment distribution decreases as a function of time. For example, in the deposition experiment with the shear stress of 0.056 N/m^2, the median size drops monotonically from 20 μm to about 10 μm which implies that larger particles settle out with minimum flocculation leading to a decrease in median size. But as shear stress increases, flocculation of the sediment in suspension becomes predominant. For example, when the shear stress is 0.121 Nm^{-2}, the D_{50} increases from 20 μm to about 25 μm. With a further increase in shear stress (0.169 Nm^{-2}), the D_{50} increases to a high of 47 μm. However, the flocs were not able to withstand the high turbulence level with subsequent increases in shear stress. Hence, smaller increases in the D_{50} can be seen for the shear stress of 0.213 Nm^{-2}. For the highest shear stress (0.324 Nm^{-2}), the D_{50} remains around the initial value of 20 μm.

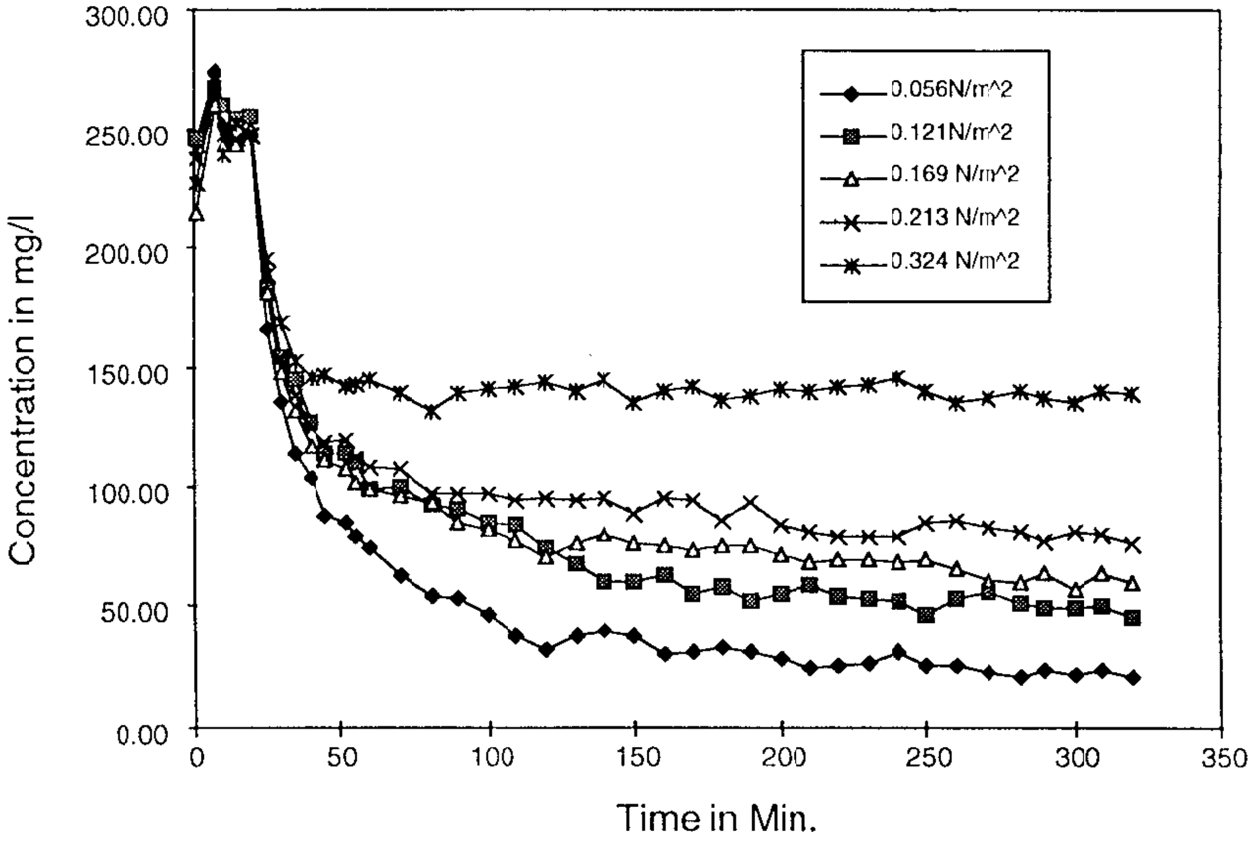


Fig. 1. Sediment concentration vs Time as a function of shear stress in deposition experiments.

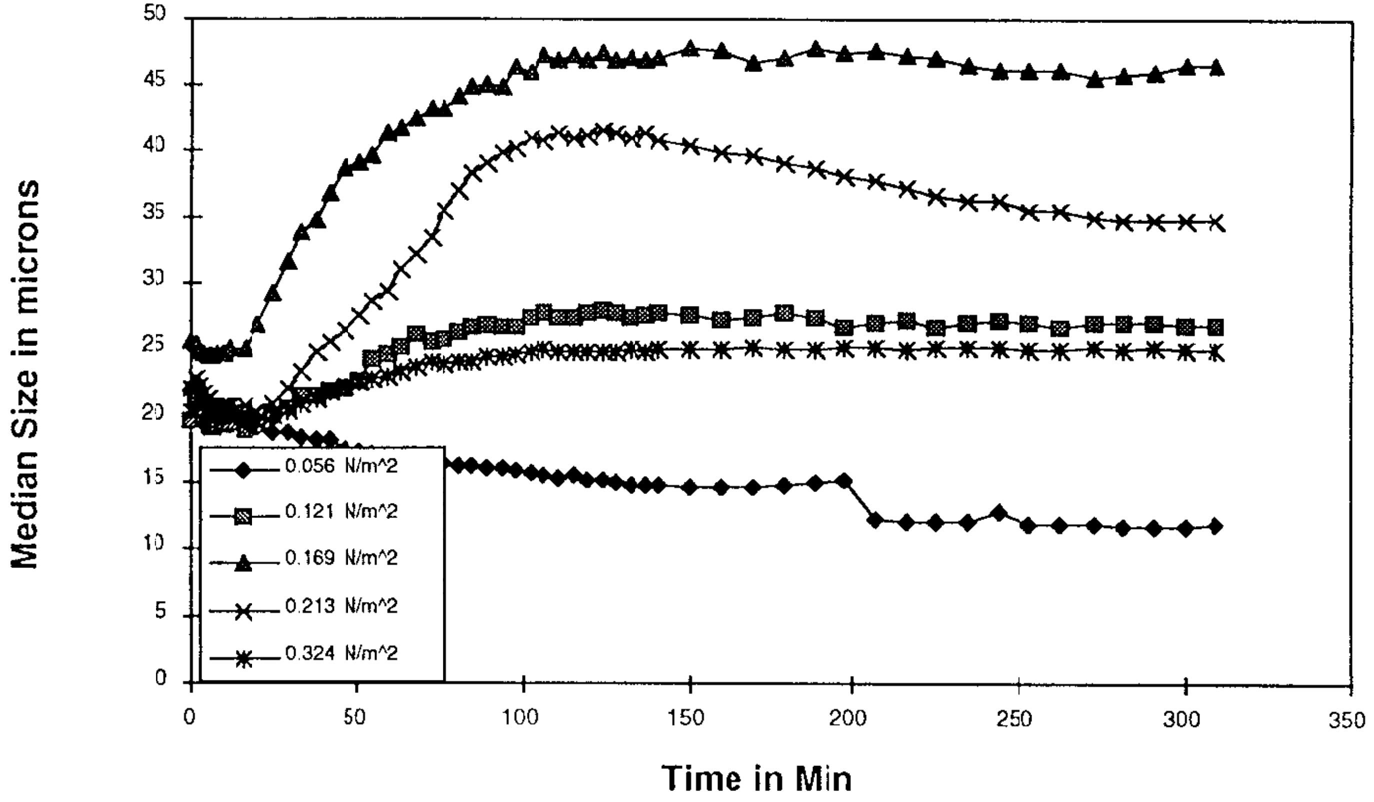


Fig. 2. The effect of shear stress on median diameter of sediment flocs in deposition experiments.

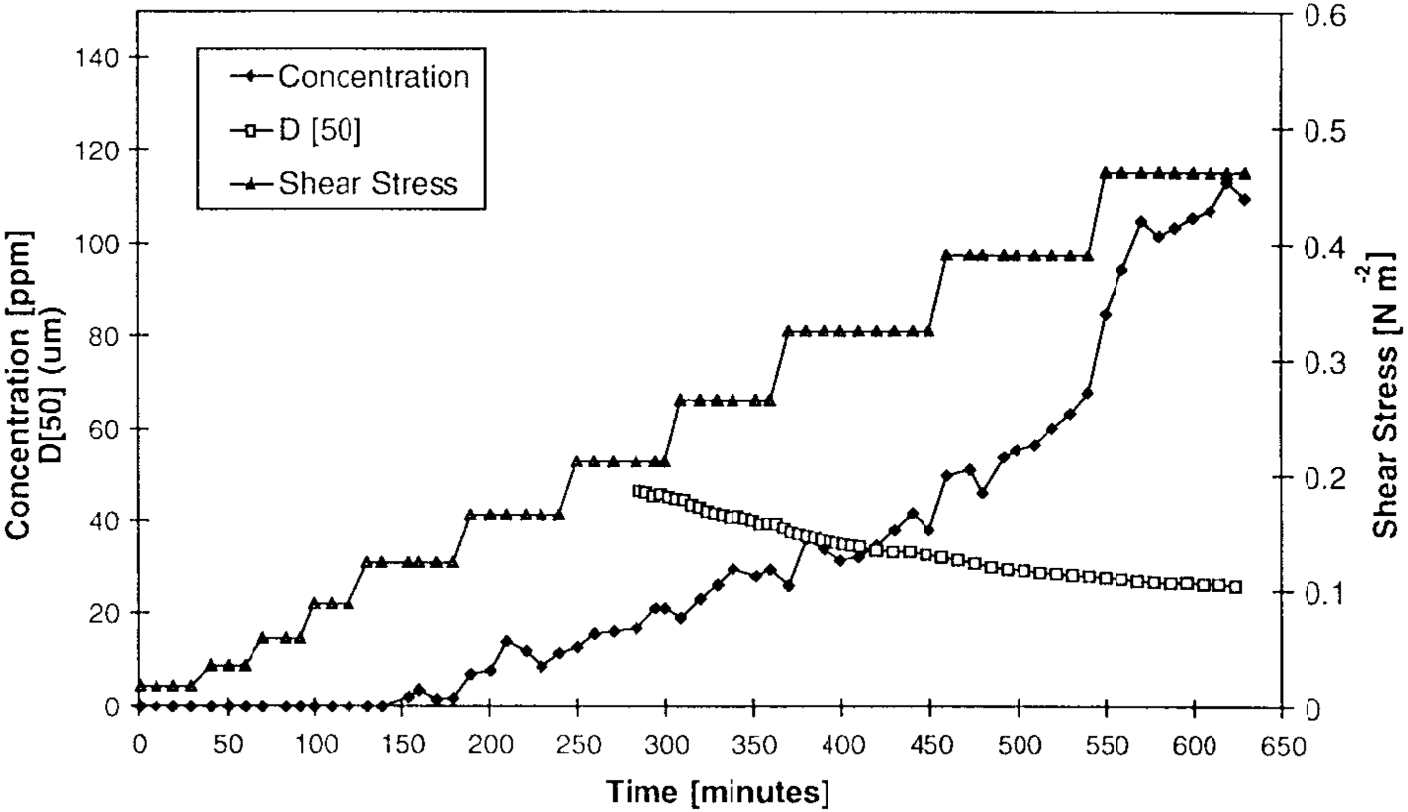


Fig. 3. Changes in sediment concentration, median diameter and shear stress as a function of time in the erosion experiment.

Table 1: Sediment Chemistry and Mineralogy (Mean and standard deviation as percent dry weight)

Sample Location	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	P_2O_5	LOI
1. Stream Sediment	63.4	8.2	3.3	2.4	4.2	1.4	2.3	0.34	0.078	0.35	14.03
Above Tile Drain	0.2	0.1	0.09	0.07	0.1	0.05	0.07	0.02	0.006	0.02	
2. Stream Sediment	49.5	5.3	2.3	4.0	17.0	1.2	1.6	0.19	0.051	0.15	18.71
Below Tile Drain	0.2	0.1	0.07	0.09	0.2	0.05	0.06	0.01	0.004	0.01	
3. Tile Drain Sediment	47.6	6.2	2.0	5.9	17.4	1.3	1.7	0.26	0.087	0.22	17.33
	0.2	0.1	0.07	0.1	0.2	0.05	0.06	0.02	0.007	0.02	
4. Surface Soils	69.7	11.0	5.8	2.8	2.6	0.99	3.0	0.52	0.180	0.66	2.75
	0.2	0.2	0.1	0.08	0.08	0.04	0.08	0.03	0.010	0.03	

Mineral Type	Stream Sediment Above Tile Drain	Stream Sediment Below Tile Drain	Tile Drain Sediment	Surface Soils
Quartz	~80	~60	~60	~80
Anorthite/Albite	5	17	15	15
Dolomite	4	10	16	—
Calcite	3	10	6	—
Other	5	3	3	3
Amorphous Organic	~3	—	—	~2

This result clearly shows that the tile-sediment has the tendency to flocculate and the flocculation process is dependent on bed shear stress.

3.2 EROSION RESULTS:

3.2.1 Concentration of the eroded sediment:

The concentrations of eroded sediment for a range of applied shear stress conditions as a function of time are shown in Fig. 3. Re-suspension of the sediment does not occur until the shear stress reaches a value of 0.121 Nm^{-2}, which is higher than the critical shear stress for deposition. Throughout the erosion experiment, higher values of shear stress levels were needed to bring concentrations comparable to the steady state concentrations that were established during the deposition experiment (Fig 2). In fact, at a shear stress of 0.462 Nm^{-2}, the re-suspended sediment concentration is about the same as the steady state concentration during deposition under a shear stress of 0.213 Nm^{-2}.

3.2.2 Size distribution of eroded sediment:

The largest D_{50} of sediment was observed at lower shear stresses and as the applied shear stress increased, the D_{50} of the eroded sediment decreased (Fig. 3). This seems to imply that the deposited sediment is flocculated and as the sediment is eroded, the flocs are dislodged from the bed and with increasing shear stress, the eroded flocs break up causing the size distribution to become finer.

3.3 SEDIMENT AND WATER CHEMISTRY:

The mineralogy and major element composition of tile drain and river sediment collected down stream of the tile outlet varies from that of surface soils and river sediment collected upstream of the tile outlet (Table 1). Due to weathering processes, tile drain sediment is depleted in Si, Al, K, Fe and P but enriched in Ca and Mg. The tile drains penetrate into the calcareous loam till which may account for the higher dolomite and calcite content observed in the drains and in the stream below the tile outlet. Compared to river sediments collected above the tile drain, increased levels of anorthite ($CaAl_2Si_2O_8$) and albite ($NaAlSi_3O_8$) are present in surface soils, tile sediments and stream sediment collected below the tile drain. This suggests that fine-grained surface materials are selectively transported through macropores into the tile drains. During subsequent irrigation or rainfall events, these fine-grained feldspar minerals will be resuspended and transported through the tiles to the stream.

The chemical characteristics of river water, tile drain water and stored river water are shown in Table 2. The higher Ca concentration in tile water is related to higher partial pressures of carbon dioxide (P_{CO2}) measured in soils which effectively lowers the solubility of calcite and promotes weathering of Ca from soils (Morel and Herring, 1993). The threefold increase of nitrate in tile water is attributed to leaching of chemical fertilizers and liquid manure applied to soils at the study site. River water collected for the flume experiments was stored at low temperature (4 °C) for 24 days. The chemistry of the river water changed during storage and lower concentrations of nitrate, sulphate and chloride were observed (Table 2). Analysis of the chemical data with the chemical equilibrium model MINEQL$^+$ showed that precipitation is not a removal mechanism for nitrate and sulphate from the water for the measured conditions

Table 2: Chemistry of River and Tile Drain Water

	Concentration (mg/L)								
Sample	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Si	Cl^{-}	NO_3^{-}	SO_4^{2-}	HCO_3^{-}
River Water	89.20	22.30	9.81	1.16	4.24	22.30	11.30	33.20	306
Tile Drain Water	106.00	21.40	7.40	0.73	4.98	12.30	44.20	20.90	305
Stored River Water	81.90	20.00	7.12	1.21	2.87	5.55	0.00	3.45	202

of pH and temperature. A second possible explanation for the observed differences is related to the reduction of nitrate and sulphate by bacteria. In waters initially containing oxygen but lacking a mechanism for reaeration, organic matter can be oxidized by, successively, dissolved O_2, NO_3 , and SO_4^{2} (Bender *et al*, 1977).

The chemical composition of flume water was measured at intervals for conditions of varying shear stress to examine potential effects of variable solution chemistry on depositional characteristics of cohesive sediments (Table 3). For all deposition experiments, the pH and concentrations of Ca, Mg, Na, K, Si, HCO_3^- did not vary (coefficient of variation, CV) by more than 5%. However, concentrations of NO_3^-, SO_4^{2-} and Cl^- were more variable (CV > 70%). This variability results from the fact that initial concentrations of NO_3^-, SO_4^{2-} and Cl^- measured in river water decreased by 100%, 90% and 75%, respectively during storage. Variation in water chemistry is also related to the order in which the depositional experiments were conducted. The first two deposition experiments were conducted on June 24 and 25, 1996 at a shear stress of 0.213 and 0.324 Nm^{-2}, respectively. During these two experimental runs, the concentration of the three anions were low (Table 3) but with successive flume runs on June 26, 27 and July 3 at a shear stress of 0.056, 0.121 and 0.169 Nm^{-2}, respectively, concentrations of NO_3^-, SO_4^{2-} and Cl^- returned to levels approximating the original chemical composition of the water (Table 2). This is likely due to reaeration of flume water where oxidation of ammonia and hydrogen sulphide would increase levels of nitrate and sulphate.

Changes in the chemical composition of flume water during erosion experiments are shown in Table 4. During this experiment, concentrations of Ca, Mg, Na, K, Si, HCO_3^- were relatively stable and generally did not vary by more than 5%. However, the concentrations of NO_3^-, SO_4^{2-} and Cl^- were more variable (41 to 49%).

4 Discussion and Conclusions

Deposition and erosion experiments in the rotating flume give quantitative information on the mode of transport of tile drain sediment when it enters the stream. If bed shear stress in the stream is less than the critical shear stress for deposition (0.056 Nm^{-2}), then all of the tile sediment entering the stream will be deposited on the stream bed. But, if the bed shear stress in the stream is greater than the critical shear stress for deposition, then only a portion of the sediment entering the stream is transported in suspension.

Table 3: Water Chemistry During Deposition Experiments. '

Date	Flume Run Shear Stress (Nm^2)	Time (*min.*)	pH	Ca^{2+}	Mg^{2+}	Na^+	*Concentration* K^+	Si	*(mg/L)* Cl^-	NO_3^-	SO_4^{2-}	HCO_3^-	DOC
June-26	0.056	10	8.48	79.00	20.00	7.05	1.19	2.69	21.90	9.59	24.70	302	3.80
		60	8.48	83.00	20.90	7.50	1.35	2.89	21.70	10.80	29.50	295	3.85
		240	8.49	80.50	20.40	7.43	1.41	2.77	20.00	10.40	28.70	299	3.77
June-27	0.121	10	8.49	81.90	21.00	7.42	1.22	2.86	20.00	9.43	27.00	286	3.76
		60	8.47	79.80	20.20	7.32	1.14	2.81	20.80	9.97	28.20	292	3.47
		240	8.49	84.50	21.60	7.73	1.30	3.00	15.10	10.70	28.30	294	3.94
July-3	0.169	10	7.69	76.30	20.50	7.30	1.18	2.81	15.20	10.90	30.00	281	3.78
		60	8.45	74.20	19.90	7.06	1.14	2.89	14.60	9.91	26.80	281	3.51
		240	8.47	79.00	21.10	7.82	1.36	2.82	12.00	5.60	16.60	280	3.90
June-24	0.213	10	8.45	81.90	20.00	7.12	1.21	2.87	5.55	0.00	3.45	302	4.03
		60	8.45	88.10	22.00	7.38	1.12	2.97	4.42	0.00	0.00	307	4.10
		240	8.45	85.60	21.50	7.05	1.13	2.87	2.36	0.00	0.00	303	4.96
June-25	0.324	10	8.45	87.20	21.50	7.22	<1.00	2.75	1.52	0.00	0.00	292	4.44
		60	8.49	80.20	20.20	6.85	<1.00	2.74	1.35	0.00	0.00	302	4.41
		240	8.45	83.20	20.70	7.08	<1.00	2.86	0.00	0.00	0.00	296	4.25

Table 4: Water Chemistry During Erosion Experiment

Flume Run						Concentration (mg/L)					
Shear Stress (Nm^2)	**pH**	**Ca^{2+}**	**Mg^{2+}**	**Na^+**	**K^+**	**Si**	**Cl^-**	**NO_3^-**	**SO_4^{2-}**	**HCO_3^-**	**DOC**
0.090	8.40	80.50	21.30	7.06	1.02	2.94	12.30	8.11	24.50	280	3.94
0.169	8.40	79.30	20.70	6.88	<1.00	2.87	44.00	22.70	63.30	290	3.60
0.259	8.41	76.10	20.10	6.68	<1.00	2.66	20.70	11.60	31.20	281	3.88
0.390	7.39	78.60	20.30	6.92	<1.00	2.94	22.00	11.20	31.90	282	4.15
0.460	8.44	77.50	20.40	7.04	1.03	2.82	22.00	12.00	32.80	240	4.14

Thus suspended tile sediments will be carried long distances within the stream depending on variations in shear stress along the length of the stream and the textural composition of the stream bed. The erosion experiments give quantitative information on the erodibility of the deposited sediment which is useful for the development of transport models of sediment in receiving streams. A modelling framework that employs such information is developed by Krishnappan (1996).

The shear stresses measured from the flume experiments can be translated into easily measurable hydraulic parameters such as the average flow velocity or the flow rate if some simplifying assumptions are made regarding the flow in the natural system. If we assume that the flow is rough turbulent and uniform, then the relationship between the average velocity and the bed shear stress becomes:

$$\frac{U}{V_*} = 2.50\,\ell n\left(11.0\frac{R}{D_{65}}\right) \tag{1}$$

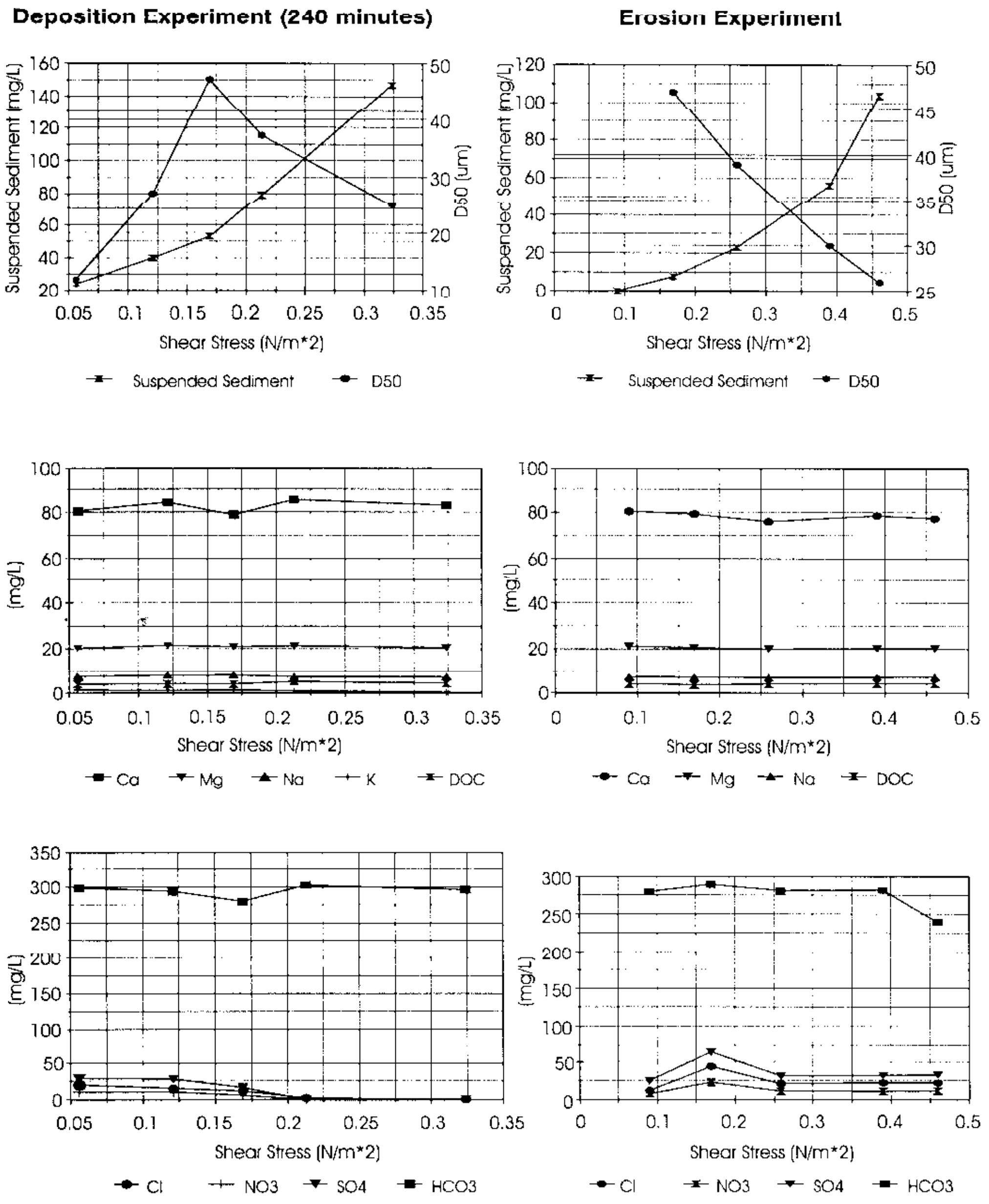
where U is the average flow velocity (ms^{-1}), *ln* is the natural logarithm, R is the hydraulic radius, D_{65} (m) is a representative size of the bed sediment and V_* is the shear velocity (ms^{-1}), which is related to the bed shear stress as follows:

$$V_* = \sqrt{\tau_0 / \rho} \tag{2}$$

Here, τ_0 is the bed shear stress (Nm^{-2}) and ρ is the density of water. Therefore, given the bed shear stress, hydraulic radius and a representative size of the bed material, the average velocity that corresponds to the bed shear stress can be calculated using equations 1 and 2.

The rotating flume experiments show that tile drain sediment has a tendency to flocculate when subjected to turbulent shear stress. This can be seen from the size distribution data measured during deposition and erosion experiments. In addition, the dual role of the turbulent shear stress in the flocculation process can also be inferred. For example, as sediment deposits in flows with low shear stress, the size distribution of the suspended sediment becomes finer and finer. This suggests that the sediment settles as individual particles resulting primarily in the settling of coarser fractions, thus leaving finer particles in suspension. As shear stress is increased, the size distribution of suspended sediment becomes coarser, which suggests that sediment particles in suspension collide and form flocs. The degree of flocculation reaches a maximum at a shear stress of 0.169 Nm^{-2}. With a further increase in shear stress, the floc sizes become smaller suggesting that the flocs are breaking up beyond the optimal shear stress for flocculation. Size distributions measured during the erosion experiments suggest that sediment eroded at lower shear stress values are coarser and as the shear stress is increased, flocs will break up causing the distribution to become finer. At high shear stress during the erosion experiment, the median size of the sediment flocs approach the size distribution established during the start of the deposition tests. The latter was produced by blending the sediment water mixture by an electric blender. This suggests that at the highest shear stress applied during the erosion test nearly all the flocs break up and the resulting size distribution can be regarded as that of primary particles.

The shear stress and the turbulence level created in the flume provide the collision mechanism, which is one of the two building blocks in the flocculation process. The second building block, namely, the coagulation mechanism is provided by either chemical coagulation or biological coagulation or both. Chemical coagulation is due to the balance between Van der Waals force of attraction and the electrostatic force of repulsion (Stumm and Morgan, 1981). The latter force is a function of the ionic strength of the suspending medium. With increasing ionic strength, the electric double layer is compressed and the electrostatic repulsion between particles is decreased (Stumm, 1992). Biological coagulation is due to polymeric fibrils secreted by bacteria which represent the dominant bridging mechanism of organic and inorganic components of flocs (Leppard, 1995; Liss *et al.* 1996). Chemical data from both deposition and erosion experiments show that pH as well as concentrations of DOC and cations remained relatively constant while the anions were more variable at various shear stress levels (Fig. 4). Ionic strength of the flume varied during erosion and deposition experiments. However, it is difficult to determine to what extent the observed changes in ionic strength can be attributed to changes in shear stress and the presence of bacteria. Still important and yet to be determined is the relative importance of bacteria and changes in solution chemistry on flocculation of the tile sediment for a range of turbulent shear stresses.



Deposition Experiment (240 minutes)

Erosion Experiment

Acknowledgements

The authors wish to thank Robert Stephens of Aquatic Ecosystem Protection Branch of National Water Research Institute for assistance with sample collection and conducting the flume experiments. The comments of Dr. H. Saunderson, Dr. G. Wall and two reviewers were greatly appreciated. Funding was provided by a Natural Sciences and Engineering Research Council (NSERC) of Canada Operating Grant held by M. Stone.

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