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Modelling sediment-microbial dynamics in the South Nation River, Ontario, Canada: Towards the prediction of aquatic and human health risk

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ABSTRACT

Runoff from agricultural watersheds can carry a number of agricultural pollutants and pathogens; often associated with the sediment fraction. Deposition of this sediment can impact water quality and the ecology of the river, and the re-suspension of such sediment can become sources of contamination for reaches downstream. In this paper a modelling framework to predict sediment and associated microbial erosion, transport and deposition is proposed for the South Nation River, Ontario, Canada. The modelling framework is based on empirical relationships (deposition and re-suspension fluxes), derived from laboratory experiments in a rotating circular flume using sediment collected from the river bed. The bed shear stress governing the deposition and re-suspension processes in the stream was predicted using a one dimensional mobile boundary flow model called MOBED. Counts of live bacteria associated with the suspended and bed sediments were used in conjunction with measured suspended sediment concentration at an upstream section to allow for the estimation of sediment associated microbial erosion, transport and deposition within the modelled river reach. Results suggest that the South Nation River is dominated by deposition periods with erosion only occurring at flows above approximately 250 $m^3 s^{-1}$ (above this threshold, all sediment (suspended and eroded) with associated bacteria are transported through the modelled reach). As microbes are often associated with sediments, and can survive for extended periods of time, the river bed is shown to be a possible source of pathogenic organisms for erosion and transport downstream during large storm events. It is clear that, shear levels, bacteria concentrations and suspended sediment are interrelated requiring that these parameters be studied together in order to understand aquatic microbial dynamics. It is important that any management strategies and operational assessments for the protection of human and aquatic health incorporate the sediment compartments (suspended and bed sediment) and the energy dynamics within the system in order to better predict the concentration of indicator organism.

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1. Introduction

Within river systems, it is clear that the microbial population (including pathogens) can be highly associated with the sediment fraction both in the suspended and bed sediment phase (Rehmann and Soupir, 2009; Krometis et al., 2007; Jamieson et al., 2004). This association serves four ecological and/or sedimentological functions; a) the sediment serves as a place for microbial attachment, b) the sediment serves as a food source (DOC, POC) for microbes, c) the sediment floc provides protection from environmental stresses (Cho et al., 2010; Gerba and McLeod, 1976) and d) bacteria and associated extracellular polymeric substances (EPS) (Leppard, 1997) promote sediment flocculation (the building of larger particles) by binding particles together to form a floc matrix, which in turn results in an increased downward flux of sediment (Droppo, 2004), and consequently associated bacteria (with possible pathogens) to the bed sediment (Droppo et al., 2010). Once on the bed, the sediment and microbes can undergo consolidation and biostabilization (biofilm development) (Droppo, 2009). As such, the bed sediment may represent a reservoir of potential pathogenic organisms with possible detrimental impacts in the event of erosion during storm flow (when the critical bed shear stress for erosion is surpassed) (Hirotani and Yoshino, 2010; Rehmann and Soupir, 2009; Wu et al., 2009). Many studies have demonstrated that bed sediment can contain orders of magnitude higher indicator organisms than the overlying water [although the suspended sediment (SS) associated microbes are not accounted for] (Cho et al., 2010; Droppo et al., 2009; Rehmann and Soupir, 2009; Crabill et al., 1999). Muirhead et al. (2004), using a series of artificial storms provided strong evidence that the bed sediment is an in-channel store of *Escherichia coli* (indicator organism) and that these stores are mobilized into the water column once erosion begins. In their experiments, three successive identical storm flows were generated on consecutive days with each yielding successively less *E. coli* (cumulative arial concentration of $1.2–1.3 \times 10^8$ cfu m^{-2}). This suggests that the bed contains a limited source of *E. coli* and further substantiates a transient microbe population whose bed concentrations are dependent on flow conditions (Muirhead et al., 2004). Cho et al. (2010) observed that there were "hot spots" of *E. coli* concentrations in the bed and that sampling could miss these important areas of potentially pathogenic organisms that may be transported during storms. As indicator organisms and pathogens have been shown to survive for extended periods of time in aquatic sediments (up to months) (Davies et al., 1995; Jamieson et al., 2005), the erosion of sediment and associated pathogens represents significant risk to aquatic and human health, particularly if the fate of the sediment/pathogens is in sensitive areas such as drinking water intakes or swimming areas (Schutze et al., 1998; Donovan et al., 2008).

Further, the association of pathogens with suspended sediment (SS) and the erosion of pathogens in association with bed sediments may result in operational sampling protocols for the assessment of human health risk being in error (Hirotani and Yoshino, 2010; Crabill et al., 1999), as such protocols assume the bacteria are planktonic in phase. In addition, samples collected for health risk assessment may not represent recent pathogenic contamination but may reflect historically deposited microbes that have been re-suspended during a high flow/shear event within a river (Ksoll et al., 2007).

There has been limited modelling of microbial transport within rivers due to the difficulties of modelling a living, changing, interactive heterogeneous organic population (microbes) (e.g. Rehmann and Soupir, 2009). For example, different microbial species will have different affinities for attachment and flocculation (Characklis et al., 2005) due in part to different quantities and type of EPS generated (Wingender et al., 1999) as well as surface charge and hydrophobicity differences (Liao et al., 2001). In addition, few models have reflected the dynamic association of the microbes with the suspended and bed sediment compartments (Cho et al., 2010; Bai and Lung, 2005; Jamieson et al., 2005). Where modelling has been attempted, generally simplistic approaches have been used which represent bacteria re-suspension and deposition in association with suspended and bed sediment with a single set of parameters (i.e. counts/g of eroded or deposited sediment). Many models require a partition coefficient to estimate the ratio of attached to free-floating bacteria. This has been done with both an irreversible adsorption process (Jamieson et al., 2005) and a reversible linear adsorption process (Bai and Lung, 2005). However, verification of these coefficients is made difficult as there are no standard methods for the differentiation of microbe counts associated with the two sediment compartments (see Droppo and Ongley, 1994; Characklis et al., 2005; Krometis et al., 2007, 2009 for non standardized methods of population separation), and an operationally defined limit of what constitutes particulate material. Cho et al. (2010) has incorporated additional reach specific parameters such as particle size distribution and critical shear stress to better assess sediment-microbe behaviour. Using these parameters, they were able to better predict the re-suspension of *E. coli* than single parameter models, although the single parameter models were better able to capture the dynamics of bacteria transport. Not accounting for the bed derived source of indicator organisms can make temporal variations in concentrations with flow difficult to model (Hellweger and Masopust, 2008). It is clear that improved model predictions of indicator organism source, transport and fate could be achieved if microbial transport models included sediment dynamics within them (Dorner et al., 2006).

In this study we link an experimental evaluation of sediment erosion and deposition fluxes with measured sediment associated live bacteria concentrations to provide an estimate of the potential for sediment to control the erosion, transport and fate of microbes and possibly pathogens in the South Nations River, Ontario, Canada. A one dimensional flow model called MOBED was used to calculate the controlling bed shear stress distribution in the river. The specific objectives of this paper are 1) to improve the prediction of pathogen mobility and fate by pairing field microbial organism counts with a mathematical model of sediment erosion, transport and fate and 2) facilitate a discussion on the need to incorporate the energy dynamics, sediment compartments and sediment

associated pathogens into the management of aquatic and human health risk.

2. Methods

2.1. Field program

2.1.1. Study site

An 8.5 km reach of the main stem of the South Nation River near Ottawa, Ontario, Canada was investigated from St. Albert to Cassleman (Fig. 1). The River drains 3700 km^2 with a very low gradient (0.5 m km^{-1}) over primarily glacial marine clay with some sandy till. The clays (Leda clays) are very unstable and prone to slope failure. The river is deep with a maximum depth measure of 8.5 m and is slow moving (<10 cm s^{-1} on average). Fig. 1 provides a bathymetric survey of the river (Knudsen 320M echo sounder with a 200 kHz transducer; Knudsen Engineering Limited). The river transports primarily fine-grained cohesive sediment with a d_{50} of 10 μm and has a bed composition ranging from gravel to cohesive glacial marine clay. Further details on the South Nation River can be found in Chapman and Putnam (1984).

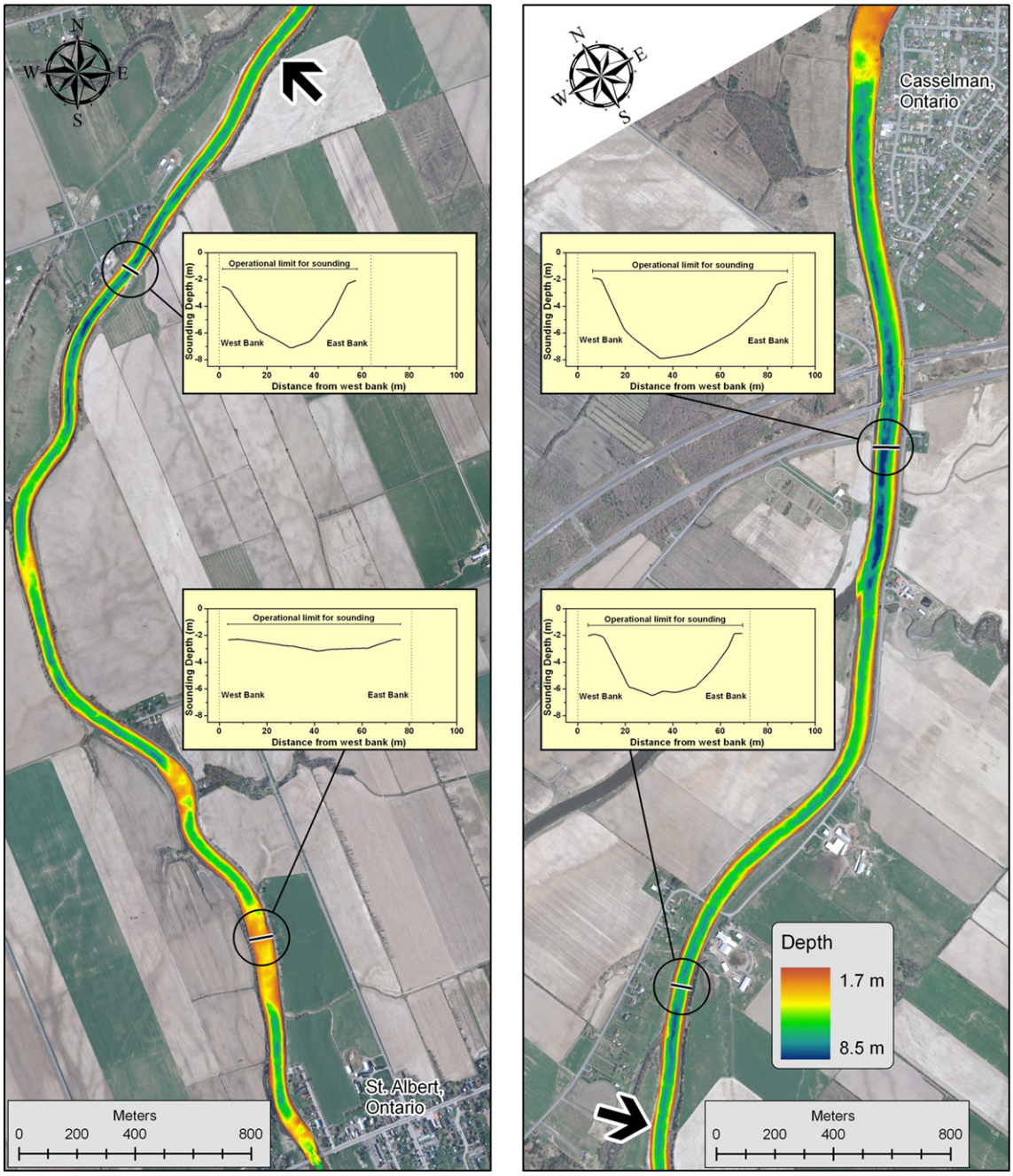

Fig. 1 – Bathymetric survey map of 8.5 km modelled reach of the South Nation River from St. Albert to Casselman, Ontario, Canada (flow from bottom to top of aerial photos). Note the deep sections of the river up to 8.5 m, in depth. Large arrows denote same location on two aerial photos.

2.1.2. SS sampling for microbial assessment

Bulk SS was collected monthly from May to November (3 samples in May) in 2006 at St. Albert using a continuous flow centrifuge (Westfalia Model KA 2-06-075) for microbial assessment and for input of SS-associated microbes into the numerical model. Samples were collected under a variety of flow and SS concentration conditions and, as such, average values are believed representative of the average open water concentrations. In this procedure bulk river water was pumped into a stainless steel bowl with a rotational speed of 9470 rpm and the denser sediment is removed from the water. The duration of pumping is dependent on the concentration of SS within the water. The majority of sediment (>90% recovery) is retained in the bowl which was then removed and placed in sterile polyethylene containers and placed on ice until analysis was performed.

2.1.3. Bed sediment sampling for microbial assessment

Bed sediment was collected on the same dates as the bulk SS samples at St. Albert for bulk grain size analysis (Sedigraph™) and surficial microbial assessment (model input) with a PONAR bed sediment sampler. Only the top few mm of sediment was scraped off the surface of the grab and placed in autoclaved polyethylene containers. All samples were kept on ice until analysis was performed.

2.1.4. Enumeration of live/lead bacteria

The microbial population (bulk average cell counts) of bed and bulk SS samples were assessed using the LIVE/DEAD® BacLight™ nucleic acid staining technique (Boulos et al., 1999). Depending on the solids concentration, 0.5 mL–5 mL of raw sample was filtered through a 0.2 μm black polycarbonate filter. One mL of 0.085% NaCl solution was placed on the filtered sample and 30 μL of a 10% dilution of LIVE/DEAD® BacLight™ staining solution (in 0.085% NaCl) was added to the mixture. The apparatus was incubated for 15 min in the dark and the dye mixture was filtered. Filters were mounted on a slide with BacLight™ mounting oil and bacteria counted (Red = dead bacteria; green = live bacteria) using a Zeiss Axiovert 100 fluorescent microscope equipped with a 520 nm barrier and 470 nm–490 nm excitation filter.

2.2. Transport characteristics of fine sediment

Deposition and erosion characteristics of fine sediments of the South Nations River were studied experimentally using a laboratory rotating circular flume. The details of the experimental program are outlined below:

2.2.1. Bed sediment sampling for laboratory flume experimentation

Sediment-water mixture from the river was collected at St. Albert using a specially designed inverted cone sediment sampler (Krishnappan, 2007). The sampler consists of an inverted cone fitted with a propeller to create sufficiently strong circulation inside the chamber to dislodge the deposited fine sediment, and a submerged pump that delivers the dislodged sediment and the water mixture to a sample container. The sampler is also fitted with a weight to stabilize it on the stream bed against the flow. The sampler was deployed at several locations within the river and the deposited sediment was collected together with the river water. About 600 L of sediment-water mixture was collected and transported to the laboratory in a refrigerated transport truck.

2.2.2. Rotating circular flume

In order to generate model parameters of erosion rate and critical bed shear stress for erosion and deposition, a rotating circular flume measuring 5.0 m in mean diameter, 0.30 m wide and 0.30 m deep was employed (Fig. 2) (Krishnappan, 1993). A counter rotating top cover (ring) fits inside the flume with close tolerance, (~1.5 mm gap on either side) and makes contact with the water surface in the flume. The maximum rotational speeds of the flume and the ring are 3 rpm respectively. The flows generated in the flume are nearly two dimensional and the bed shear stress distribution across the width of the flume is fairly uniform (Krishnappan and Engel, 2004). The flume calibration results of Krishnappan and Engel (2004) were used to predict the relationship between the bed shear stress and the rotational speeds of the flume assembly.

2.2.3. Deposition experiments

River water was placed in the flume with a known amount of sediment (approximately 350 mg L^{-1}). The sediment-water suspension was then thoroughly mixed in the flume first by mechanical mixing and then by rotating the flume and the lid at relatively high speeds (2.5 rpm for the lid and 2.0 rpm for the flume, which yielded a bed shear stress of 0.6 Pa) for 20 min. Following this mixing period, the flume speed was turned down to a lower rate of shear and maintained for the duration of the experimental run. Shear values used were 0.059, 0.126 and 0.217 Pa. Sediment-water samples were withdrawn from the flume at 5 min intervals during the first hour of the test and every 10 min thereafter until the completion of the test. Each time a sample was withdrawn, the volume removed was replaced by adding an equivalent amount of sediment-water mixture back into the flume, in order to keep the water surface in contact with the lid all the time. A test was considered to be completed after the SS concentration remained nearly constant for about 1 h (generally requiring 5 h for most runs).

Sediment-water samples were analysed for concentrations of solids by a gravimetric method which consisted of filtering the sample (0.45 μm pre-weighed Millipore filter), and drying and weighing the residue. Once the test had been completed, the whole procedure was repeated for other flume speeds.

2.2.4. Erosion experiment

Additional South Nation River bed sediment was added to the flume which was then mixed at a high rate of speed to thoroughly mix the sediment and water. The flume speed was then gradually reduced to a stop to allow the mixture to settle and consolidate/biostabilize. This formed a bed of approximately 2 cm depth. The flume and the lid were then set in motion and their speeds were incrementally increased in 50 min time intervals. At each interval, sediment samples

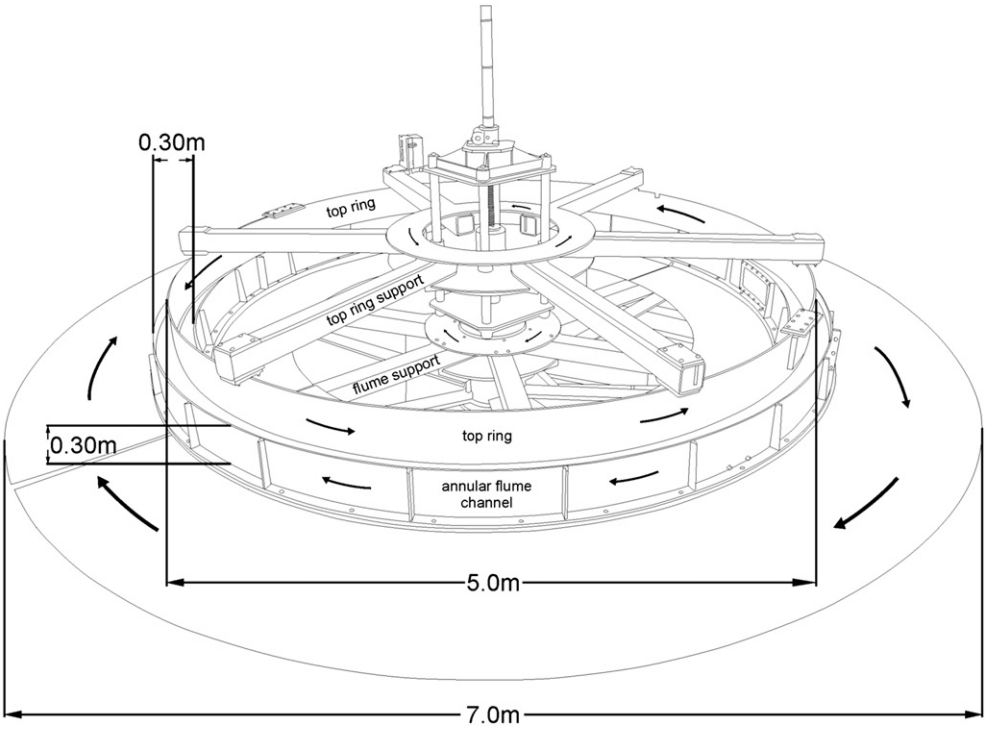

Fig. 2 – Schematic representation of the rotating circular flume.

were collected every 10 min to measure the SS concentration variation as a function of time (as above, sample volumes removed were immediately replaced). When the sediment concentration reached a steady state value, the flume speed was increased to the next level (for our experiment this occurred until the shear reached just over 0.2 Pa). This procedure was carried out over three different consolidation/biostabilization periods of 22.5, 45 and 92 h.

3. Results and discussion

3.1. *Deposition characteristics*

Fig. 3 illustrates the SS concentration in the water column as a function of time for three different bed shear stresses during deposition. For all runs the SS concentration decreases rapidly followed by a steady state (equilibrium) concentration for each bed shear stress. For example, for the lowest bed shear stress tested (0.059 Pa), the steady state concentration was about 50 mg L^{-1} (17% of the initial concentration), whereas for the highest shear stress (0.217 Pa), the steady state concentration was about 250 mg L^{-1} (83% of the initial concentration). If the bed shear stress was slightly lower than 0.059 Pa, then all the initially SS would have deposited. Such a bed shear stress was defined as the critical shear stress for sediment deposition, which for the South Nation River sediment was considered to be 0.050 Pa.

The deposition tests also offer a quantitative measure of the amount of sediment that is likely to be transported through the river for given flow conditions. For example, if the flow conditions in the river are such that the bed shear stress in the river is less than the critical shear stress for deposition, then all of the sediment and associated bacteria entering the river would deposit to the river bed. On the other hand, if the bed shear stress reaches 0.217 Pa, then about 83% of the suspended material and associated bacteria would be transported in suspension. Knowing the flow field and the spatial and temporal variation of the bed shear stress, along with the SS-associated bacterial counts, the results from the deposition tests can be used to make quantitative estimates of sediment and bacteria deposition to the river bed.

3.2. *Erosion characteristics*

Fig. 4 illustrates the SS concentration profiles for three different consolidation/biostabilization periods with increasing shear stress. For the more stabilized beds (45 and 92 h consolidation/biostabilization), the sediments are relatively stable at a shear stress of 0.09 Pa with erosion not occurring until the shear reached 0.123 Pa. In this work we use the conservative number of 0.09 Pa to represent the critical shear stress for erosion of the surface sediment layer. Contrary to previous results (Droppo, 2009) the least consolidation/biostabilization sediment (22.5 h) did not show erosion occurring until an increment higher (0.165 Pa). This anomaly is likely related to the higher initial SS concentration in suspension at the start of the test, masking erosion. It should be noted however that, as expected, later in the erosion sequence the weakest bed (22.5 h consolidated/biostabilized) yielded the highest SS concentration, while the oldest, most stabilized sediment bed resulted in the lowest SS concentration. At each

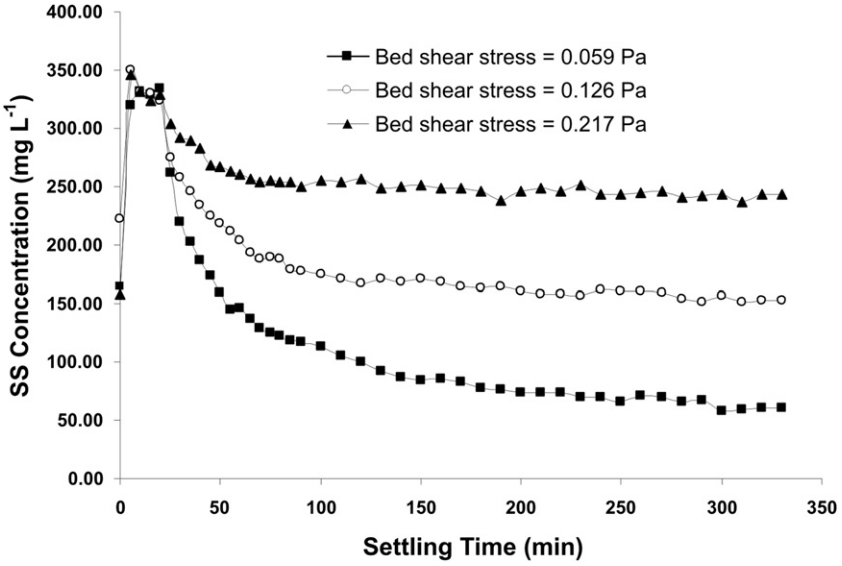

Fig. 3 – Results from deposition experiments.

step in shear stress, SS concentration increased gradually and showed a tendency to approach a steady state value. As such, increasing shear stresses were required to erode deeper material and to continue to increase the SS concentration. Such a trend is suggestive of increasing bed strength with depth and is likely related to a combination of self-weighted consolidation and biostabilization (Droppo, 2009). At the maximum shear stress of 0.21 Pa, not all of the deposited sediment was re-suspended. The maximum concentration reached was only 60 percent of the total concentration that would have resulted from complete re-suspension. The maximum concentration that was attained at the shear stress of 0.21 Pa was about the same as the steady state concentration observed in a deposition test at a much lower shear stress of 0.126 Pa. It is important to note that the critical shear stress for erosion is larger than the critical shear stress for deposition, which is a distinguishing characteristic of cohesive sediment (Lick, 1982; Parchure and Mehta, 1985). The difference in critical shear stresses has implications for the transport behaviour of cohesive sediments.

3.3. *Derivation of sediment transport functions*

The results of the present experimental investigation show that the sediments from the South Nation River behave like cohesive sediments and hence the modelling of sediment transport in the river has to take into account the cohesive sediment transport characteristics. The difference between the cohesive and cohesionless sediment transports results from the fact that the critical shear stresses for erosion and deposition are equal for cohesionless sediments, and hence such sediments undergo simultaneous erosion and deposition when subjected to a constant bed shear stress. On the other hand, for cohesive sediments, these two stresses are not equal and therefore, the sediment flocs do not undergo deposition and erosion simultaneously. A deposited sediment floc will

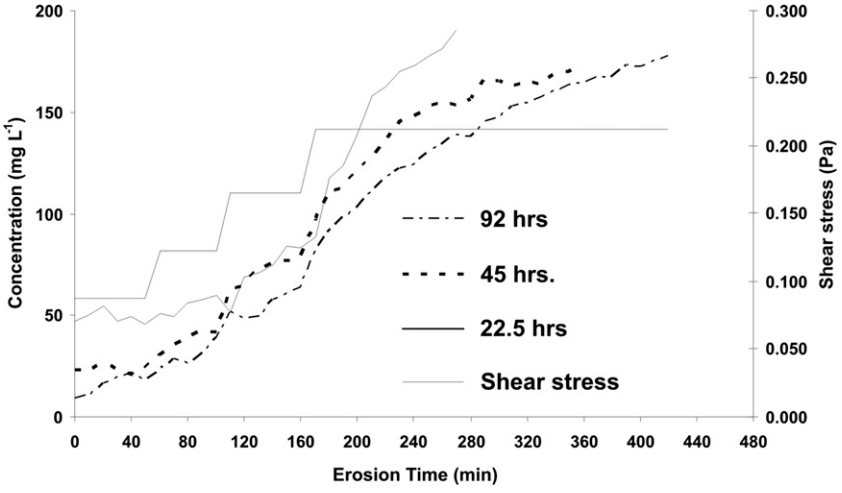

Fig. 4 – Results from erosion experiments.

remain on the bed until it is exposed to a higher shear stress that exceeds the critical shear stress for that sediment floc (Lau and Krishnappan, 1994). A mathematical model reflecting this distinction was developed by Krishnappan (2000) for stream flows and is applied in this study.

In the quasi-steady state model proposed by Krishnappan (2000), deposition and erosion functions were determined from the deposition and erosion experiments, respectively, and these functions were used to quantify the vertical exchange of sediment at the sediment/water interface for different bed shear stress conditions.

The deposition function (Fig. 5), derived from the results of the deposition experiments as well as from previous experiences with other cohesive sediments tested in the flume (Stone and Krishnappan, 1997; Skafel and Krishnappan, 1999 and Milburn and Krishnappan, 2003), gives the fraction of the deposited sediment as a function of the bed shear stress. The bed shear stress is normalized using the critical shear stress for deposition. This function satisfies the condition that when the bed shear stress is less than the critical shear stress for deposition, then all of the initial SS is deposited, i.e. the fraction deposited equals one. When the normalized bed shear stress is greater than 5.5 (corresponding to a shear stress value of 0.275 Pa), then none of the initial SS deposit, i.e. the fraction deposited is equal to zero. When the bed shear stress is within these two limits, then the fraction of sediment deposited is given by the power function below:

$$\begin{aligned} f_d &= 1.0 - 0.43(\tau_0/\tau_{cd} - 1)^{0.543} \text{ for } \{1 < \tau_0/\tau_{cd} < 5.5\} \\ f_d &= 1.0 \text{ for } \{\tau_0/\tau_{cd} \le 1\} \\ f_d &= 0 \text{ for } \{\tau_0/\tau_{cd} \ge 5.5\} \end{aligned} \quad (1)$$

where f_d is the fraction deposited, τ_0 is the bed shear stress and τ_{cd} is the critical shear stress for deposition.

The erosion function (Fig. 5) reflects the fact that the critical shear stress for erosion is 1.8 times the critical shear stress for deposition and the shear stress that is needed to erode 100% of the deposited sediment is 14 times the critical shear stress for deposition (which corresponds to a shear stress value of 0.70 Pa and obtained by extrapolating the erosion function to a value of 1). Therefore, for the bed shear stress lower than 1.8 times the critical shear stress for deposition, none of the deposited sediment will be eroded (i.e. the fraction of sediment eroded is equal to zero). For shear stresses greater than 14 times the critical shear stress for deposition, all of the deposited sediment will be eroded (i.e. the fraction of the sediment eroded equals one). The analytical form of the erosion function is as follows:

$$\begin{aligned} f_e &= 0.3(\tau_0/\tau_{cd} - 1.8)^{0.523} \text{ for } \{1.8 < \tau_0/\tau_{cd} < 14\} \\ f_e &= 0 \text{ for } \{\tau_0/\tau_{cd} \le 1.8\} \\ f_e &= 1 \text{ for } \{\tau_0/\tau_{cd} \ge 14\} \end{aligned} \quad (2)$$

where f_e is the erosion function.

The above two power law type relationships describing deposition and erosion processes of South Nation River sediment were similar to the ones used to describe the transport of several other cohesive sediments tested in the rotating circular (Krishnappan, 1996; Stone and Krishnappan, 1997; Skafel and Krishnappan, 1999; Milburn and Krishnappan, 2003). Even though the form of the power law remains the same for all these sediments, the coefficients defining the power law, the ratio between the critical shear stress for erosion and deposition and the actual value of the critical shear stress for deposition differ from sediment to sediment. These properties have to be determined empirically using site specific sediments in flumes such as the one used in the present study.

Since the bed shear stress is normalized using the critical shear stress for deposition, care should be taken to determine the latter accurately, as any error in its determination will propagate through the calculation of the sediment and bacteria fluxes at the sediment-water interface. In the present measurements, the accuracy of sediment dynamic parameters is in the range of 10–15%, which is well within the accuracy of measurements related to bacteria. Ideally, future models will need to incorporate microbial partitioning, inactivation and growth in order to have dynamic models capable of simulating the complex interaction between microbes, sediment and hydrodynamics. Work by Gao et al. (2011) is progressing towards this end.

Using these two functions, sediment and the associated live bacteria transported through the river can be calculated by dividing the river into a number of segments and calculating the sediment and bacteria mass balance through these segments knowing the flow field calculated using the MOBED model. Details of these calculations are given below.

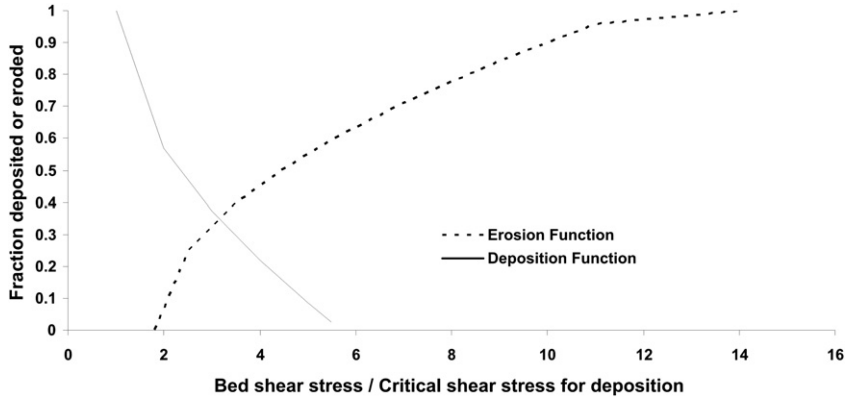

Fig. 5 – Deposition and Erosion functions for the South Nation River sediment.

3.4. Sediment mass balance

The river reach is divided into a number of segments shown schematically in Fig. 6.

The flow rate (Q ($m^3 s^{-1}$)) in each segment is considered to be steady. For a varying flow, a quasi-steady state is assumed and the flow hydrograph is approximated by a step function. The average bed shear stress (τ_0) has to be determined for each segment as a function of the flow rate. This will be done using a mobile boundary flow model, MOBED.

For each segment, the range of the flow rates over an average year is established and the corresponding boundary-shear stress range is calculated. This shear stress range is then divided into a fixed number of flow stages. Each flow stage is identified with its own average boundary-shear stress which is the mean value of the shear stresses bounding the range. To be consistent with the sediment transport functions given by Equations (1) And (2), the boundary-shear stress is normalized using the critical shear stress for deposition.

3.5. Mass balance of sediment in a control segment

3.5.1. SS inflow

The mass balance of the sediment in a control segment is calculated as follows: SS entering the control segment can be 1) from the upstream segment and 2) from tributary inflows (although for this simulation we assumed no tributaries). The amount of SS (q_{su}) entering the control segment during a time interval of Δt can be expressed as follows:

$$q_{su} = QC_{i-1}\Delta t + Q_t C_t \Delta t \tag{3}$$

where C_{i-1} is the SS concentration in the upstream segment, C_t is the concentration of SS in the tributary inflow to the control segment and Q_t is the tributary inflow rate.

3.5.2. SS depositing to the bed

A portion of the incoming SS will deposit depending on the prevailing flow conditions. The SS quantity transported from the upstream segment will be deposited only when the shear stress in the control segment is lower than that in the upstream segment. If the shear stress in the control segment is equal to or greater than the upstream segment, then the SS arriving from the upstream segment would have gone through the deposition process already and would have reached the steady state concentration. Therefore, this SS has to be routed straight through the control segment. The amount that would deposit in the control segment, therefore, can be calculated as:

$$q_{sd} = (QC_{i-1}\Delta t)f_d + (Q_t C_t \Delta_t)f_d \quad if\ \tau_I \le \tau_{I-1} \tag{4}$$

$$q_{sd} = (Q_t C_t \Delta t)f_d + (QC_{I-1}\Delta t) \quad if\ \tau_I \rangle \tau_{I-1} \tag{5}$$

where q_{sd} is the amount deposited during the current time step.

The amount remaining in suspension (q_{ss}) becomes:

$$q_{ss} = (QC_{i-1}\Delta t + Q_t C_t \Delta t)(1 - f_d) \quad if\ \tau_I \le \tau_{I-1} \tag{6}$$

$$q_{ss} = Q_t C_t \Delta t (1 - f_d) \quad if\ \tau_I \rangle \tau_{I-1} \tag{7}$$

3.5.3. Sediment re-suspension

Sediment can also be re-suspended from deposits that occurred in previous time steps. The mass of re-suspended sediment can be calculated by keeping track of the amount of deposited sediment and the shear stresses at which deposition takes place. This can be done by schematizing the river bed to consist of different compartments and assuming that each compartment holds sediment deposited at a particular shear stress. For example, let us assume that there are N compartments in the control segment and each compartment is identified with an index, say, J. Therefore, J varies from 1 to N. Compartment 1 is assumed to collect sediment deposited at shear stress equal to or less than the critical shear stress for deposition, τ_{cd}, and compartment 2 collects sediment deposited at shear stresses between τ_{cd} and $2\tau_{cd}$ and so on. Let the sediment deposited in each of the compartments from the previous time steps be P_J. For a given shear stress, the sediment re-suspended from various compartments can be calculated by applying Equation (2) for each compartment with the appropriate τ_{cd} value as follows:

$$q_{sr} = \sum_{J=1}^{N} q_{srJ} = \sum_{J=1}^{N} P_J f_{eJ} \tag{8}$$

where q_{sr} is the total amount of re-suspended sediment and f_{eJ} is the erosion function for the compartment J.

Knowing the amount of sediment re-suspended from and deposited to the bed, the concentration of the SS and the

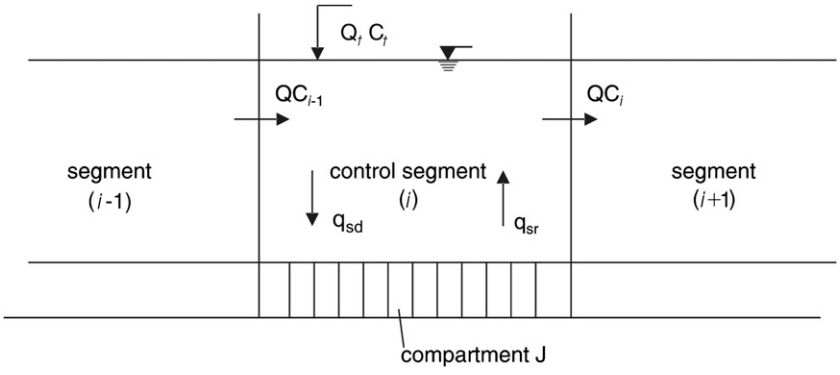

Fig. 6 – Schematic representation of sediment mass balance.

amount of sediment in the various compartments in the bed of the control segment at the end of the current time step can be calculated as follows:

3.5.4. *SS concentration at the end of the current time step*

The SS concentration in the control segment at the end of the current time step is:

$$C(i) = \frac{(q_{ss} + q_{sr})}{(Q\Delta t)} \quad (9)$$

3.5.5. *Amount of sediment in various bed compartments at the end of the current time step*

The amount of sediment left behind in the control segment at the end of the current time step is:

$$\sum_{J=1}^{N} P_J^* = \sum_{J=1}^{N} P_J\left(1 - f_{ej}\right) + \delta(J,K) * q_{sd} \quad (10)$$

where P_J^* is the updated value of P_J at the end of the current time step. The function $\delta(J,K)$ takes a value of unity, when $J = K$, and zero when $J \neq K$. K denotes the compartment which receives the deposited sediment during the current time step.

The concentration $C(i)$, as calculated by Equation (9), is routed to the downstream segment and the calculations outlined above for the control segment are repeated for the downstream segment. The process is continued until all the segments are accounted for. The calculations are then repeated for the next time step until the simulation period is covered.

3.6. *Sediment associated bacteria mass balance*

Knowing average live bacterial concentrations for SS floc and in the bed sediment, an equation for the bacteria concentration associated with sediment in the water column can be derived from the SS concentration equation, i.e. Equation (9). Denoting the bacteria concentration in SS as N_{ps} (counts mg^{-1} of SS) and the bacteria concentration in bed sediment as N_{pb} (counts mg^{-1} of bed sediment), the equation for the bacteria concentration contributed to the water column via the sediment phases N_p (counts L^{-1} of water) can be derived as follows:

$$N_p = \left(q_{ss}N_{ps} + q_{sr}N_{pb}\right)/(Q\Delta t) \quad (11)$$

The above equation can be applied for all segments of the river and for all time steps to compute the transport of bacteria associated with sediment.

3.7. *Flow computation using MOBED Model*

Flow characteristics in the receiving stream were modelled using the MOBED model developed by Krishnappan (1980). MOBED is an unsteady and mobile boundary flow model based on a generalized friction factor relationship and hence is suitable to predict the flow characteristics. Input data to the model include cross sectional geometry of each transect, initial bed and water surface elevations, boundary conditions at the upstream and downstream sections of the study reach and mobile bed roughness parameters. Measured cross sectional shapes at 18 sites were used in the model. The initial bed level along the length of the stream reach was determined from the thalweg at each cross section and the values between the measured sections were linearly interpolated. The initial water surface elevation was obtained by running the model as a steady state model.

A 2005 spring melt flow hydrograph from the Cassleman gauging station (02LB013) was used in the modelling exercise to represent the flow entering the upstream boundary at St. Albert (Fig. 7). The model was run for this flow hydrograph and the bed shear stress as a function of distance along the stream and time were calculated. The shear stress variation as a function of time for the peak flow of 600 $m^3\ s^{-1}$ and at a lowest model flow of 100 $m^3\ s^{-1}$ is shown in Fig. 8 as an example.

A full routing of sediment and associated bacteria can be made using the complete solution of the MOBED model. The initial model input variable of SS concentration ($C_{initial}$) for the first segment at St. Albert was calculated by applying the discharge date from Fig. 7 to a rating curve (Equation 12) determined from June SS concentration and discharge

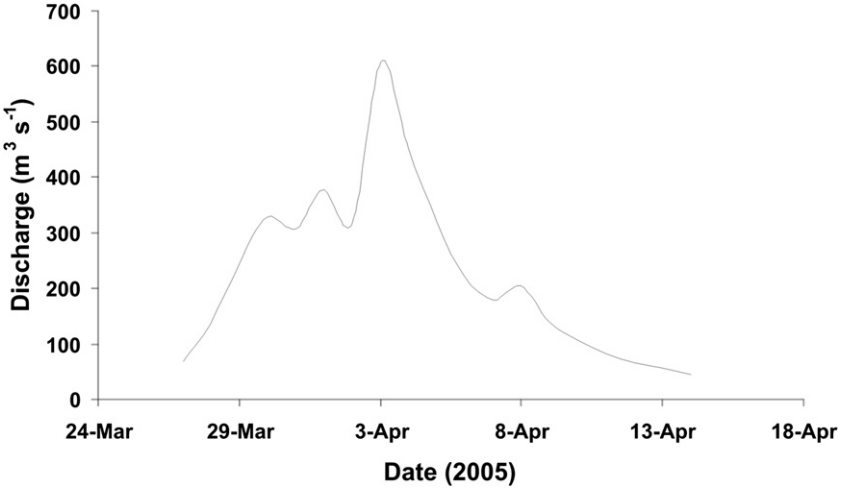

Fig. 7 – Flow hydrograph used at the upstream boundary.

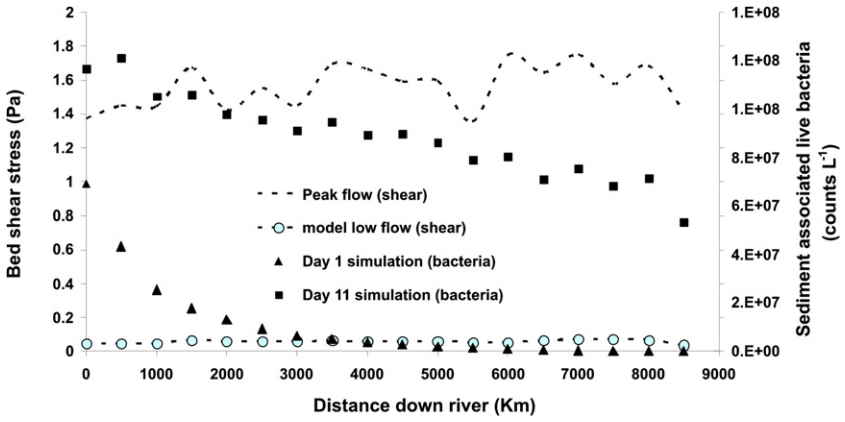

Fig. 8 – Dashed lines are predicted shear stress variation over the modelled reach for the peak flow (600 $m^3 s^{-1}$) and for the lowest model flow (100 $m^3 s^{-1}$). Solid symbols are predicted change in *Np* (contribution of live bacteria concentrations associated with sediment per L of water) for the first day of simulation (100 $m^3 s^{-1}$) and during the falling limb on day 11 (200 $m^3 s^{-1}$).

measurements from historical SS data (1971–2001 – Plantagenet sediment gauging station 02LB005) (only April data was used for the model as this is the month of our data sampling and the time for which high flows occur in the river – Fig. 7).

$$C_{initial} = 26.01 \times Q^{0.25} \quad (12)$$

3.8. *Sediment associated bacteria transport in South Nation River*

Model outputs using Equation 11 are illustrated in Fig. 8 for day 1 and 11 of the simulation over the 8.5 km modelled reach. It was observed that initially when modelled flows are low (100 $m^3 s^{-1}$), the majority of bacteria associated with the SS are delivered to the bed with counts at the 8.5 km transect depleting to 1.3×10^5 counts L^{-1} from an initial calculated input value of 6.8×10^7 at St. Albert. At this point the bed shear stress is very close to the critical bed shear stress for deposition and sediment and associated bacteria are being deposited under the low flow conditions. At flows above approximately 250 $m^3 s^{-1}$, there is no deposition and only erosion takes place routing all sediment associated bacteria through the modelled reach as bed shear levels are 5.5 times greater than the critical bed shear stress for deposition (0.05 Pa) (See Fig. 5). Concentrations increased from 2.3×10^7 counts L^{-1} at a flow of 260 $m^3 s^{-1}$ to 4.0×10^8 counts L^{-1} at 600 $m^3 s^{-1}$. Only after the falling limb declined to below 250 $m^3 s^{-1}$ did bacteria associated with the SS begin to deposit again. For example, after 11 days, (discharge = 200 $m^3 s^{-1}$), bacteria is still being transported through the modelled reach (Fig. 8), however, deposition is occurring as seen by the decrease in concentration with distance down river. This reduction in concentration is related to the shear level variations allowing partial settling with the ratio of bed shear stress to critical bed shear stress for deposition fluctuating intermediately between 1 and 5.5. Given that the mean annual flow at Casselman (02LB013) is only 29.3 $m^3 s^{-1}$ (flows above 250 $m^3 s^{-1}$ have only been recorded for spring melt periods), it is clear that for the majority of the year the river is depositing microbes associated with the SS to the river bed; thus facilitating the bed as a reservoir of pathogens for potential downstream transport with a significant storm or spring melt flood event.

3.8.1. *Implications of sediment associated bacteria to aquatic and human health*

The model, while simplistic in that tributary inputs and historic sediment deposits are not accounted for (i.e. only the sediment entering the system for transport, deposition and erosion is considered in this model), provides evidence that river sediment dynamics can play a very strong role in controlling the microbial and possibly pathogen dynamics within river systems. The model shows that river bacterial dynamics can be highly influenced by the erosion, transport and deposition of sediment. Bacteria and pathogens have been shown to be orders of magnitude higher in association with sediments (both bed and suspended) with the bed sediment representing a significant reservoir of possible pathogenic organisms (Hirotani and Yoshino, 2010; Droppo et al., 2009; Muirhead et al., 2004; Obiri-Danso and Jones, 2000). Pathogens are known to live for up to several months within bed sediment (Davies et al., 1995; Obiri-Danso and Jones, 2000; Jamieson et al., 2005) and, as such, the determination of indicator organism counts for the assessment of aquatic and human health risk, may not only represent contemporary contamination but also historically deposited microbes (Ksoll et al., 2007). Currently, source area tracking of pathogenic organisms investigate mostly terrestrial sources without due consideration of the river bed as a possible source of pathogens during erosion events (Droppo et al., 2009). Further, a current lack of understanding around the dynamic processes involved with sediment/microbial interactions has lead to current indicator organism monitoring by health departments (for the assessment of human health risk) to assume that bacteria are planktonic in nature. This ignores the fact that a large proportion of the bacteria in suspension can be associated with the SS (Droppo et al., 2010; Crabill et al., 1999). The above assumption is somewhat necessitated by the lack of a standardized test for determining the contribution of

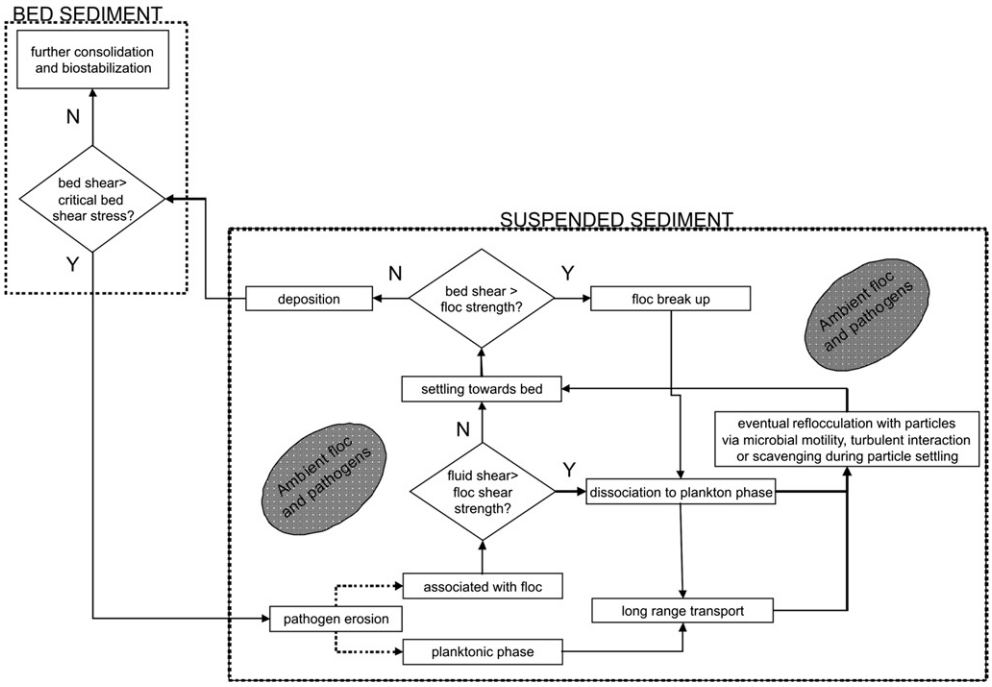

Fig. 9 – A schematic diagram demonstrating the relationship between pathogen and sediment dynamics within river systems (modified from Droppo et al., 2010). Erosion, deposition and suspended floc-pathogen dynamics are portrayed in relation to the ambient floc and pathogens populations held in suspension.

microbes from sediment compartments. It is important that such a test be made available and be used across health departments in the future. In addition, typical sampling designs do not take into account the linkage of the energy (shear) regime (e.g. currents, waves) with sediment/pathogen dynamics (i.e. flow dependent concentrations of bacteria), but report counts per volume at a point in time.

From the modelling exercise and the above discussion, it is apparent that the dynamics of microbes (including pathogens) within river systems are influenced by 3 domains; 1) flow regimes, 2) sediment properties and 3) microbial community characteristics and behaviour. The interactions of these domains are demonstrated in Fig. 9 (modified from Droppo et al., 2010). This model provides a simplified conceptualization of the numerical model above and is centred on three decision boxes operating within the ambient floc-pathogen population held in suspension within the river. These boxes are responsible for routing pathogens between the bed sediment, SS (floc) and the planktonic phase as influenced by the energy regimes at the sediment-water interface and within the water column. The directional decision boxes of the model are related to: (1) bed shear stress relative to critical bed shear stress which dictates if pathogens will be eroded from the bed in planktonic or floc attached modes, or further consolidated and multiplied in the bed sediment/biofilm; (2) fluid shear relative to floc shear strength which dictates if pathogens will be dissociated from the floc or eventually settle towards the bed in association with the floc; and (3) bed shear stress relative to floc shear strength which dictates if the floc will remain intact and deliver pathogens to the bed, or if it will break up resulting in pathogen dissociation and longer range transport. The transitory nature of pathogens (i.e. associated with the bed, floc, or planktonic under different energy conditions) will have implications for the potential risk to aquatic and human health. Fig. 9 and the results of the modelling confirm the need to understand the energy regime in relation to both the sediment and associated microbes (pathogens) within the water column. Monitoring programmes intended to assess risk to human health which currently neglect the sediment phase of pathogen existence, and the energy regime they preside in, may provide management decisions which are erroneous with possible detrimental impacts. As such, it is critical that management protocols and policy development for the protection of aquatic and human health include a consideration of both the SS and bed sediment indicator organism population.

4. Conclusions

Experiments carried out in a rotating circular flume with sediment from the South Nation River indicate that the river sediment exhibits cohesive behaviour. As such, a cohesive sediment transport model in conjunction with a mobile boundary flow model was used to predict SS and associated live bacteria transported within the South Nation River. The modelling provided a first order estimate of the influential impact of suspended and bed sediment on the dynamics of pathogens in a river system.

For a given flow condition, the proposed modelling framework predicted the bed shear stress variation along the river reach and thereby facilitated the computation of erosion,

transport and deposition of SS and sediment associated bacteria concentrations and rates along the river reach. Over the modelled hydrograph and 8.5 km reach, live bacteria were found to be eroded from the bed and transported through the system at flows above approximately 250 $m^3 s^{-1}$. For flows below this level (the norm for the South Nation River), there was significant deposition suggesting that the bed of the South Nation River is likely a substantive source of pathogens for subsequent erosion and transport down river to potentially environmentally sensitive areas (e.g. recreational areas and drinking water intakes). While the work provided in this paper is specific to the geometry, flow conditions, sediment dynamics and measured microbial counts of the South Nation River, the modelling framework, proved to be a useful tool to assess the impact of sediment and bacteria transport, erosion and deposition within the South Nation River. The algorithms used in the model are transferable to other rivers, however, the coefficients defining the power law, the ratio between the critical shear stress for erosion and deposition and the actual value of the critical shear stress for deposition differ from sediment to sediment. As such, these variables would need to be determined empirically for each system studied.

It is clear that, shear levels, bacteria concentrations and SS have a symbiotic relationship within riverine systems. One can not be studied without accounting for the influence of the others. In this regard, it is important that any management strategies and operational assessments for the protection of human and aquatic health incorporate the sediment compartments (SS and bed sediment) and the energy dynamics within the system in order to better predict the concentration of indicator organism.

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