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Hydrological factors affecting spatial and temporal fate of sediment in association with stream crossings of the Mackenzie Gas Pipeline

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Research documents are produced in the official language in which they are provided to the Secretariat.

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ABSTRACT

This paper provides a review of processes involved in the transport and deposition of river sediment as the foundation for the development of a sedimentation algorithm to be incorporated into the Fisheries Risk Assessment Tool (FRAT). The FRAT contains algorithms for sediment entering stream channels due to natural processes and pipeline construction activities. The fate of sediment once it enters stream channels is not part of the current version of the FRAT. Sedimentation may be investigated in one of two ways: a forward physical approach or an inverse morphological approach. The first involves using known physics to predict sedimentation. The second is an inverse approach that uses the observed properties of the stream channel to infer sediment transport and depositional processes. This paper first reviews the forward physical approach through the introduction of the energy terms that are known to drive sediment transport and the terms that resist entrainment. Sediment in rivers is transported in two modes: as bedload and as suspended load. Bedload is coarse material and is defined as the material that moves in contact with the bed. No universally applied bedload transport function exists after more than one hundred years of research. However, a number of approaches to bedload transport have been investigated and are introduced. Suspended sediment is defined as the material that is transported within the water column. Fundamentally, deposition of suspended sediment occurs when the fall velocity of the sediment is greater than the turbulent eddies suspending the sediment within the water column. The inverse approach, using channel morphology to provide information on the antecedent condition of the channel is discussed along with a description of channel patterns. Literature on sedimentation related to pipeline construction and the fate of sediment introduced to northern rivers are introduced. The final section discusses measurable variables for the development of a sedimentation algorithm.

Facteurs hydrologiques qui ont une incidence sur le devenir spatial et temporel des sédiments liés aux traversées de cours d'eau du gazoduc de la vallée du Mackenzie

RÉSUMÉ

Le présent document examine les processus à l'œuvre dans le transport et le dépôt de sédiments fluviaux en vue de mettre au point un algorithme pour la sédimentation qui sera intégré à l'outil d'évaluation des risques liés aux pêches. Cet outil contient des algorithmes qui décrivent l'entrée dans le chenal de cours d'eau de sédiments issus de processus naturels et des activités de construction du gazoduc. La version actuelle de l'outil ne rend pas compte du devenir des sédiments une fois entrés dans les chenaux de cours d'eau. Il y a deux approches pour étudier la sédimentation : l'approche physique de prévision et l'approche morphologique inverse. La première a recours à la physique connue pour prévoir la sédimentation. La deuxième déduit le transport des sédiments et les processus de dépôt à partir des propriétés observées du chenal de cours d'eau. Le présent document examine d'abord l'approche physique de prévision par l'introduction des termes relatifs à l'énergie qui sont censés favoriser le transport des sédiments et ceux qui l'entravent. Le transport des sédiments dans les rivières se fait de deux manières : comme charge de fond et comme charge suspendue. La charge de fond est constituée de matériaux grossiers qui se déplacent en contact avec le fond. Après plus de cent ans de recherche, on ne dispose toujours pas de fonction universelle du transport de la charge de fond. Cependant, on a étudié un certain nombre d'approches au transport de la charge de fond; le présent document les présente. Par sédiments en suspension, on entend les matériaux transportés dans la colonne d'eau. Le dépôt des sédiments en suspension se fait essentiellement lorsque la vitesse de chute des sédiments est plus élevée que celle des remous qui maintiennent en suspension les sédiments dans la colonne d'eau. L'approche inverse, qui a recours à la morphologie du chenal pour déduire son état antérieur, est analysée tout comme la description des tendances du chenal. Le document présente les études sur la sédimentation causée par la construction de gazoducs et le devenir des sédiments introduits dans les rivières du Nord. La dernière section analyse les variables mesurables pour élaborer un algorithme de calcul de la sédimentation.

BACKGROUND

The Fisheries Risk Assessment Tool (FRAT) as developed by Fisheries and Oceans Canada (DFO) currently contains provisions for the introduction of sediment to streams from sources such as landslides, bank erosion, and pipeline construction. There remains however, uncertainty in the program as to the fate of sediment once introduced into a stream at the crossing location. This is a working paper on the hydrological factors that affect sediment mobility and transport in streams. Specifically, it intends to describe what factors are likely to influence the residence time and mobility of sediment as it relates to fish habitat in the Mackenzie River and tributaries.

OBJECTIVES

The objectives of the paper are to:

1. provide a literature review and summary of the hydrologic factors affecting sediment mobility and transport in Northern Canadian Rivers;
2. determine hydrological parameters likely to be useful and measurable in the evaluation of the fate of introduced sediment to the Mackenzie River and tributaries, and evaluate the pros and cons of each measure; and,
3. provide a summary of how algorithms can be developed to include the spatial/temporal fate of sediment downstream of river crossings.

INTRODUCTION

To predict the susceptibility of sedimentation within a given reach one needs to know something about the capacity of the channel to transport the material through the reach. The problem of understanding the fate of sediment and therefore sedimentation may be investigated in one of two ways: a forward physical approach or an inverse morphological approach. The first involves using known physics to predict sedimentation. The second is an inverse approach that uses the observed properties of the stream channel to infer sediment transport and depositional processes (Church 2006).

The forward approach can be used to predict the susceptibility of a river section to sedimentation on the bed. The size and volume of background sediment supplied to the channel and the capacity of the channel to transport sediment downstream can be estimated. Sediment within rivers is transported through two main mechanisms: as bedload and suspended load (Knighton 1998). Suspended load is material transported within the water column; while bedload is transported on the channel bed (Figure 1). The transport mechanics and therefore the fate of bedload and suspended load differ and are considered separately. By understanding the mechanics of sediment transport and sedimentation, the variables most useful to the prediction of downstream sedimentation may be determined.

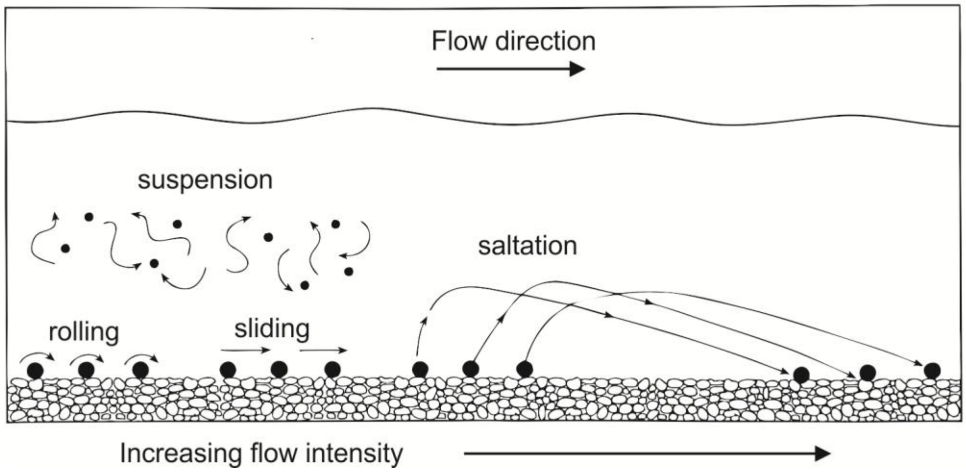

Figure 1. Cartoon diagram showing rolling, sliding, saltation and suspension of fluvial sediment [after Fryirs and Brierley (2013)].

The inverse approach uses channel morphology to provide information on the antecedent condition of the channel (Church 2006). Channel morphology provides an integration of past conditions of sediment input, discharge, etc. It also provides information on the transport capacity of the channel: supply limited channels have greater transport capacity than transport limited channels. A description of channel patterns is provided to support the inverse method.

The philosophy in writing the document is to provide a review of the factors that control sediment mobility, transport and sedimentation. This review forms the basis for identification of measurable variables for potential inclusion in a sedimentation algorithm in the FRAT. The paper has six main sections, beginning with a discussion on the controls on sediment mobility and transport, followed by sections on bedload and suspended load transport and deposition. The next sections discuss bed sedimentation, sedimentation related to pipeline construction and the fate of sediment introduced into northern Canadian rivers. Finally, approaches to define the measurable variables that can be used for algorithm development are discussed.

PREDICTING SEDIMENTATION CONTROLS ON SEDIMENT MOBILITY AND TRANSPORT

Fundamentally, sediment transport processes control the fate of sediment in river systems. Fluvial sediment transport has been investigated for more than a Century. The results fill the pages of hydrology, engineering and geomorphology books and journals. At the time of writing, Google Scholar returned more than 1 million articles when given the term ‘Sediment Transport’. A comprehensive review of sediment transport is therefore, beyond the scope of this paper. Instead, we introduce the reader to widely accepted sediment transport definitions, models and methods that can be used to understand the fate of sediment once it enters a stream. The hydrological factors most commonly measured are then refined to consider what is practical and useful to measure in the northern Canadian environment for an application such as the FRAT.

The fate of sediment, once it enters a stream channel is first understood by the capacity of the channel to transport sediment from one location to another, either locally within a single reach, or from reach to reach. Transport capacity refers to the maximum amount of sediment (in volume or weight) that can be entrained and transported by a stream channel for a specific discharge (Chang 1998) and it varies both spatially and temporally. When the sediment supply exceeds channel transport capacity, deposition occurs.

The following sections describe the factors that control the stability of river beds and therefore will provide a starting point in the review of the factors that control sedimentation on river beds.

River beds are stable when there is a balance between driving forces and the factors (framework) resisting that erosion. Sedimentation or erosion occurs when there is an imbalance between the driving forces and the resisting framework within a stream channel. Lane (1957) proposed a function to describe the balance:

$$\boldsymbol{QS} \propto \boldsymbol{Q_s} \mathrm{D}_{50}$$

Where: Q is the water discharge, S is the bed slope, Q_s is the sediment discharge, and D_{50} is the median sediment size. This function, termed Lane's Law, balances the driving forces on one side against the resisting framework on the opposite side (Figure 2). The following sections describe how to estimate each component.

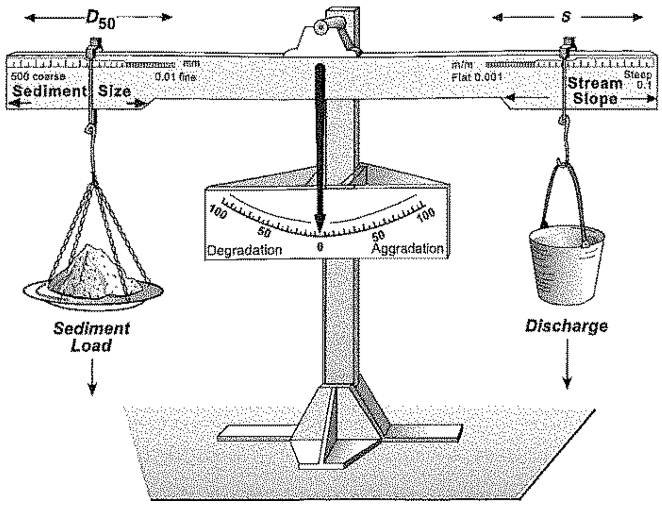

Figure 2. Diagram of Lane's Law showing the driving forces on the right side of the scale and the resisting framework on the left side of the scale (from Fryirs and Brierley 2013).

DRIVING FORCES

Lane's law (1957) illustrates that the driving forces in river channels increase with larger slope and greater discharge. Bankfull discharge (Q_{bf}) is commonly used as the dominant channel forming flow (Leopold and Wolman 1957), occurring when the river stage reaches the floodplain level (Dunne 1978; Williams 1978). The return period of bankfull discharge has been shown to approximate a 1.5-year event (Castro and Jackson 2001; Dury et al. 1963; Leopold et al. 1964); however it may range from 1- to 32-years (Williams 1978). The energy at the channel bed available to do work, calculated using the channel slope and discharge, is represented by stream power (Ω, Wm^{-1}):

$$\boldsymbol{\Omega = \rho g Q S}$$

Where: Q is water discharge, ρ is the density of water, and g is the gravitational constant (Knighton 1998; Chang 1998). A related energy term is specific stream power (ω, Wm^{-2}):

$$\boldsymbol{\omega = \frac{\rho g Q S}{w} = \frac{\Omega}{w}}$$

Where: Ω is normalized by w, channel width (Knighton 1998; Chang 1998). An additional term describing the driving force is the shear stress at the bed ($\boldsymbol{\tau_o}$, Pa):

$$\boldsymbol{\tau_o} = \boldsymbol{\rho g R S} = \frac{\boldsymbol{\omega}}{\boldsymbol{v}}$$

Where: *R* is the hydraulic radius (*R* = *A*/*P*, where *A* is the channel area, *P* is the wetted perimeter) and *v* is the cross-sectional average velocity (Knighton 1998; Chang 1998).

As is shown above, a related variable to driving force is velocity (v, ms^{-1}) because as velocity increases, shear stress and stream power generally increase. Velocity can be estimated using Manning's equation:

$$\boldsymbol{v} = \frac{\boldsymbol{R^{\frac{2}{3}} S^{\frac{1}{2}}}}{\boldsymbol{n}}$$

Where: n is Manning's resistance factor (Fryirs and Brierley 2013).

RESISTING FRAMEWORK

The resisting framework balances against the driving forces to limit sediment entrainment and transport (Brierley and Fryirs 2005). One important aspect of the resisting framework is grain size of the bed sediment. Material with larger grain size offers more resistance to transport than smaller material. Lane's Law uses the median grain size (D_{50}) to describe this effect. However, several other measurable parameters are used to describe the grain size, including D_{16} and D_{84} (the 16th and 84th percentile of the cumulative grain size distribution, respectively). For areas where it is impractical to measure grain size directly, like downstream of all crossings, grain size (D_{50}) can be estimated using a technique developed by Buffington et al. (2004) using:

$$D_{50} = \frac{(\rho \alpha A^{\beta} S)^{1-n}}{(\rho_s - \rho) k \, g^n}$$

Where: k and n are empirical values that vary with channel type and local catchment conditions, A is the drainage basin area, α and β are empirical values representing local physiography (geology, topography and climate), basin hydrology and sediment supply, and g is the gravitational constant.

The critical shear stress ($\boldsymbol{\tau_c}$) is the threshold of shear stress on the bed required to initiate motion of a particle. The most common method used to relate particle grain size to the critical shear stress is the Shields equation (Shields 1936):

$$\tau^* = \frac{\boldsymbol{\tau_c}}{(\boldsymbol{\gamma_s} - \boldsymbol{\gamma})\boldsymbol{D_{50}}}$$

Where: τ^* is the Shields parameter, γ_s is the specific weight of sediment and γ is the specific weight of water (*ρg*). For gravel bed rivers, the Shields parameter typically ranges from 0.03 to 0.073 (Buffington and Montgomery 1997).

The other factor from Lane's Law (1957) is the sediment load (Q_s) or the total volume of sediment transported by a stream channel. Determination of sediment load can be complicated and is discussed in subsequent sections. A simple relation using the sediment discharge (Q_s) as a function of discharge (Q) is called a sediment rating curve:

$$Q_s = aQ^b$$

Where, *a* and *b* are coefficients (Wilcock et al. 2009). A dimensionless rating curve has been developed by dividing Q_s by bankfull discharge (Q_{bf}) (Wilcock et al. 2009). Assuming that the coefficient *a* does not vary with Q_{bf}, this eliminates *a* from the equation. Some authors have suggested average values for the exponent b [e.g., Rosgen (2007)], however b varies from one river to another and is not predictive (Wilcock et al. 2009) but may be calibrated for individual sites.

SEDIMENT BUDGETS

Sediment load is not constant downstream and the effect of increasing sediment input to a stream bed can be accessed through the development of a sediment budget for a reach. The sediment budget can be defined as:

$$\Delta \boldsymbol{Q_s} = \boldsymbol{Q_{s\,in}} - \boldsymbol{Q_{s\,out}}$$

Where: ΔQ_s is the change in sediment volume within a reach, $Q_{s\,in}$ is the sediment entering a reach, and $Q_{s\,out}$ is the sediment exiting a reach (Figure 3). Where ΔQ_s is equal to zero the bed is stable (termed in grade), ΔQ_s is positive when the bed is aggrading (bed level increasing/sedimentation) and where ΔQ_s is negative when the bed is degrading (bed level decreasing/erosion).

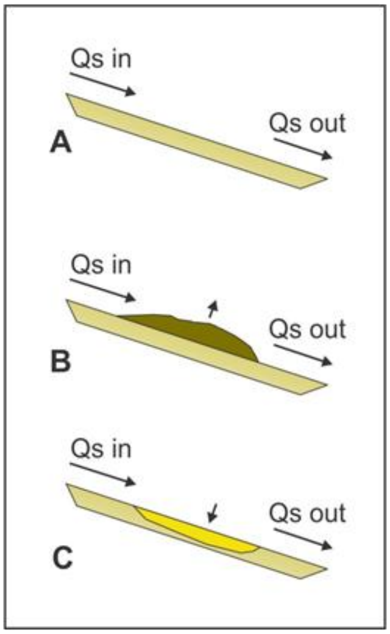

Figure 3. (A) Downstream sediment discharge patterns for a stable river bed that is in grade ($Q_{s\,in} = Q_{s\,out}$). (B) Downstream sediment discharge patterns for an aggrading river bed ($Q_{s\,in} > Q_{s\,out}$). (C) Downstream sediment discharge patterns for a degrading river bed ($Q_{s\,in} < Q_{s\,out}$). (from Burge and Guthrie 2013).

SUMMARY

Lane's Law describes the driving forces and the resisting framework that influence the stability of river beds. These forces can be expressed in several ways, but slope, discharge and channel shape variables (e.g., width, depth) are used to calculate the driving forces; grain size and sediment supply are used to describe the resisting framework. The change in sediment discharge ΔQ_s is useful for predicting sedimentation. Ideally, all inputs and outputs to the reach would be known to predict ΔQ_s. Sediment discharge (Q_s) can be divided into the bedload component (Q_{bed}) and the suspended load component (Q_{ss}) (Benda and Dunne 1997). The next sections will discuss bedload transport, followed by a discussion of suspended load transport.

BEDLOAD TRANSPORT

Sedimentation on a channel bed is controlled by the sediment transport dynamics within the reach. A discussion therefore follows on bedload transport and the estimation of bedload transport rates, different sediment patterns and bar types.

After more than a hundred years of research on bedload transport there remains no universal equation that provides a reliable estimate of the transported bed material in a flood. The size of the material transported depends on sediment input, sediment distribution and channel energy characteristics but, the bedload fraction is always the material that moves in contact with the channel bed (Bravard and Petit 1997). In gravel-bed rivers, displacement of particles occurs by different means depending on the duration of the contact between the river bed and the particle. Generally speaking, sediment particles can move by saltation (little jumps in the water column), rolling or sliding (Figure 1) (Drake et al. 1988).

Most of the theories on bedload transport have been developed from flume experiments where flow is steady and uniform (Lavelle and Mofjeld 1987; Gomez 1991). These experiments use a reductionist approach and do not translate well to the natural environment, especially in gravel-bed rivers where bed forms affect the flow at different spatial scales (Buffington and Montgomery 1997; Barry et al. 2004). Since the 1990s, the scientific community has attempted a diversified approach to bedload transport (Gray et al. 2010) and it is argued that a combination of a deterministic approach and a stochastic process is better suited to the understanding of bedload transport processes (Habersack 2000). Because of the non-cohesive nature of the bed material, the resistance to entrainment offered by the particle depends on its physical characteristics such as size, shape, mass, shape of particles around it and the bed structure. The particle remains on the bed by its weight while the forces that lead to the incipient motion are a combination of the drag that acts tangentially to the particle and the lift force. Drag is created by the friction of water and lift is created by pressure differences around the particle. Entrainment is proportional to the shear velocity, μ^* where:

$$\mu^* = \sqrt{\frac{\tau_o}{\rho}} = \sqrt{gRS}$$

Gravel-bed rivers are characterized by bed material with a wide range of particle sizes. The structure of the bed and the presence of various particle sizes make for complex relationships between particle size and the force needed for particle entrainment. Small particles will need higher force than expected to be entrained when they are shielded by larger particles, while larger particle can be entrained at lower force when they are protruding in the flow (Bravard and Petit 1997).

Bedload transport can be divided into three phases (Ashworth and Ferguson 1989). Each phase of transport is a function of bedload transport intensity and exceedance above the critical threshold of particle entrainment of the median particle size ($\boldsymbol{\tau_c}$). In phase I, only a few grains move along the bed. In phase II, particles are entrained with size-selection; successively larger particles are entrained by larger shear stresses. In phase III, also termed equal-mobility, all grain sizes transport together at high rates of shear stress (Ashworth and Ferguson 1989).

Generally, bedload transport follows a power relationship with a mean hydraulic variable. However, the response of the bedload is highly variable within a flood (Garcia et al. 2000) and from one flood to another (Reid et al. 1985). This can be explained by the intermittent nature of bedload transport. Variables that cause intermittency in gravel-bed rivers include: bed armour, sediment supply and sediment waves. Because of these variables, bedload transport is discontinuous even in steady flow conditions; one set of hydraulic conditions does not lead to one transport response (Gomez 1991). The intermittency is characterized by periods of intense transport rates and periods of low transport rates that return periodically (Figure 4) (Gomez and Church 1989; Gomez 1991).

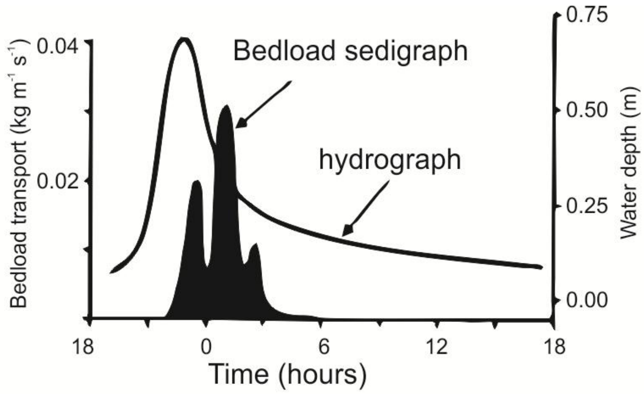

Figure 4. Example of bedload pulses measured on Turkey Brook in southern England (from Reid et. al. 1985 and Thorne et al. 1997).

This pulsation pattern of the bedload transport rate is seen over various time scales, from seconds to a season (Gomez 1991). Gomez and Church (1989) associated the peak of the pulsation to the movement of bedforms. The bedload transport signal is composed of movement at different time scales caused by the movement of individual particles and the displacement of bedforms where the amplitude is higher for the lower frequency part of the bedload process (bedforms). The intermittent nature of bedload transport changes with flow conditions (Singh et al. 2009). At low flow conditions, bedload transport is very intermittent (Phase I) and it tends to be less intermittent when flow conditions are higher (Phase II or III).

As gravel-bed rivers are composed of particles over a wide size range, the bedload rate is calculated for different sizes in the mixture. Bed material size is typically characterized using a cumulative frequency distribution of grain-size. The proportions of the size fractions are used to calculate the transport rate. If the bed mixture of the gravel-bed river contains more than 40% sand, it is said that the bed is matrix-supported. When the bed has less than 25% sand, the bed is said to be framework-supported (Wilcock et al. 2009).

An additional factor is that gravel-bed rivers exhibit vertical sorting (Figure 5). Surface material is coarser than the sub-surface material. The surface layer is therefore termed the armour layer because it has the effect of increasing the critical shear stress necessary for entrainment. The composition of the transported material is generally finer than the surface layer and closer to that of the sub-surface material (Fryirs and Brierley 2013).

Figure 5. Cartoon drawing showing the surface and subsurface layers in a gravel-bed river (from Fryirs and Brierley 2013).

CALCULATION OF BEDLOAD TRANSPORT RATES

Sedimentation can be predicted using the forward approach through the calculation of sediment transport rates. Unfortunately, sediment discharge is notoriously difficult to measure and even more difficult to predict (Burge and Guthrie 2013). Sampling bedload transport is difficult because most of the sediment transport occurs during high flow events. There are, however, tools that can be applied to measure and model sediment transport to estimate sediment discharge.

Equations of bedload transport attempt to predict the sediment transport rate based on a mean hydraulic variable (shear stress, stream power, velocity). This assumes a specific relationship between the two variables (Gomez and Church 1989). Most deterministic equations use a threshold for incipient motion (τ_c) related to the flow variable. Sediment transport rates can be estimated as a function of the excess force applied to the bed. The selection of the hydraulic variable between stream power, shear stress and velocity is still subject to some debate because there is inconsistency in the trend of bedload transport regarding the variation of these variables with bed roughness (Annandale 2006). A mean value for the hydraulic variable is used because the equations were developed using data from physical models (flumes) where local hydraulic conditions are well represented by mean flow variables (Gomez 1991). However, in natural channels the flow is three dimensional and changes in the cross-stream and vertical dimensions because of different bed features. These conditions create non-uniform flow and most models cannot account for a non-uniform flow term.

Bedload transport rate is generally defined as the volume of sediment transport per unit of channel width (Wilcock et al. 2009). Termed the unit sediment discharge (q_s), it is influenced by both flow and bed material variables. Generally, unit sediment discharge can be defined as a function of the force of the water (τ_o), water depth (*d* or *y*), grain size (*D*), specific water density (γ), sediment density (γ_s) and water viscosity (μ). Almost all bedload formulae belong to one of three types in which the unit transport rate is related to either:

i. excess shear stress $(\tau_o - \tau_c)$ $q_s = X'\tau_o(\tau_o - \tau_c)$ [Du boys type]

ii. excess discharge/unit width $(q_o - q_c)$ $q_s = X"S^{3/2}D^{-1/2}(q_o - q_c)$ [Schoklitsch type]

iii. excess stream power/unit width $(\omega_o - \omega_c)$ $q_s \cong (\omega_o - \omega_c)^{\frac{2}{3}}\, d^{-\frac{3}{2}}\, D^{-\frac{1}{2}}$ [Bagnold (1980)]

Where: *X′ and X″* are sediment coefficients, *d* is flow depth, *S* is slope and *D* is grain size. An example of an equation that uses excess shear stress is the Meyer-Peter and Müller Equation (Meyer-Peter and Müller 1948):

$$q_s = 0.253\ (\tau_o - \tau_c)^{\frac{2}{3}}$$

Where: q_s is the unit sediment transport rate (kg m^{-1}). Other examples include Bagnold (1977) and Bagnold (1980), which used specific stream power and critical specific stream power to model sediment transport rates in sand bedded channels (Robert 2003).

Another way to look at sediment transport is to use the path length (how far a particle travels during transport). The governing equation for spatially averaged bedload transport rate using path length, modified from the definition of Einstein (1950), can be written as:

$$g\ = rL/t$$

Where *g* is the rate of bedload transport (weight) per unit channel width (kg m^{-1} s^{-1}), *r* is the weight of the eroded material per area of bed (kg m^{-2}), *L* is the mean path length (m) and *t* is elapsed time (s) (Pyrce and Ashmore 2003).

Stochastic theory says that bedload transport is best described by probability laws because of its intermittent nature. Einstein (1950) defined bedload transport as the sum of individual particle movements characterized by a path length and rest period in between successive movements. Pryce and Ashmore (2003) provide a summary of studies of particle path lengths; they found that path length was often related to channel morphology; channels with riffle-pool morphology had modes in path length related to the distance between barforms or riffles. Since the distance between barforms scales with channel width, transport distance also scales with channel width. In general, frequency distributions of path length are skewed (Ergenzinger and Schmidt 1990; Schmidt and Ergenzinger 1992; Habersack 2001; McNamara and Borden 2004) and their shape becomes flatter with increasing discharge. The mass of the particle has not been found to control path length (Ergenzinger and Schmidt 1990), and the resting time between particle movement decreases with increasing stages, leading to less intermittent bedload transport (Habersack 2001).

SUMMARY

Deposition of bedload occurs where the transport capacity is lower than the sediment input to a reach. Bed sediment transport capacity is governed by the bedload transport rates. No universal bedload transport law exists. Bedload transport rates are stochastic and vary through time, even at the same discharge (Gomez 1991). Bedload transport rates are related to excess shear stress, stream power, or unit discharge (Knighton 1998). The variables used to predict bedload transport are the same as or are related to the variables that describe the driving forces and resisting framework described in the first section.

SUSPENDED LOAD TRANSPORT

The second mechanism of sediment transport occurs within the water itself. Suspended sediment is transported within the water column and generally consists of relatively fine sediment (sand to clay). Cohesion may be important as it leads to aggregation of particles (Mehta and McAnally 2007). Fundamentally, suspended sediment is transported as upward turbulent water motion supports suspended sediment in the water column (Church 2006). Deposition occurs where the fall velocity of a particle is greater than the turbulent motion holding the sediment within suspension. The fall velocity of a particle can be calculated using:

$V_o = \frac{1}{18} D^2 g \frac{\rho_s - \rho}{\mu}$ for silt and clay < 0.0063 mm (Stokes' Law)

$V_o = \sqrt{\frac{2}{3} D g \frac{\rho_s - \rho}{\rho}}$ for gravel > 2 mm

Where: V_o (m s^{-1}) is the settling velocity, D (mm) is the grain size, ρ_s is the sediment density (assumed to be 2650 kg m^{-3}), ρ is the water density (1000 kg m^{-3}) and μ (N s m^{-2}) is the dynamic viscosity (affected by temperature). For sand, a composite law can be derived based on particle *size* (Table 1) (Fryirs and Brierley 2013).

Table 1. Fall velocity for sand-size sediment in still water at 20^{o}C. (from Fryirs and Brierley 2013).

Grain Size D (mm)	*Wentworth Scale*	*Fall velocity V_o (m s^{-1})*
0.089	*Very fine sand*	*0.005*
0.147	*Fine sand*	*0.013*
0.25	*Medium sand*	*0.028*
0.42	*Medium sand*	*0.050*
0.76	*Coarse sand*	*0.10*
1.8	*Very course sand*	*0.17*

Water velocity and grain size were related to the entrainment, transport and deposition of suspended sediment by Hjulstrom (1939) through the development of two curves: one for entrainment and one for deposition (Figure 6). The depositional curve shows the velocities at which sediment of a given size will deposit. Note that there is a large difference between the entrainment curve and the depositional curve for fine sediment. This means that sediment will be entrained at a much higher velocity than it will be deposited. This leads to sediment suspended in the water column often being deposited a long distance from the source area (Church 2006). However, deposition may also occur in a downstream pool or riffle depending on the local velocities at the time.

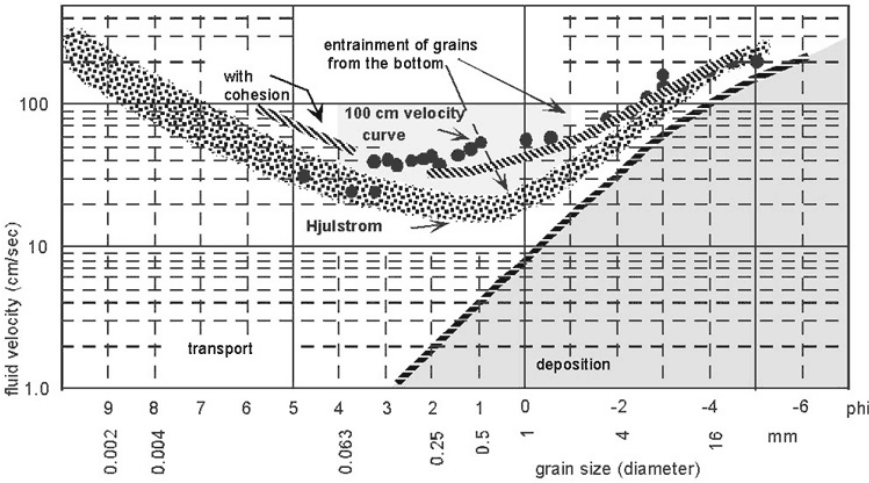

Figure 6. Curve by Hjulstrom (1939) showing the zones of entrainment, transport and deposition for a given velocity and grain size.

The concentration of suspended sediment is generally several orders of magnitude below its sediment transport capacity (Knighton 1998). Therefore, the dominant control on suspended sediment concentration is the rate of supply. Suspended sediment concentrations change throughout a storm hydrograph and throughout the year (Figure 7). These temporal changes may create a hysteresis because the rate of fine sediment supplied to the flow is greater during the rising limb of the hydrograph compared to the falling limb (Robert 2003). Sediment deposited and stored on the channel bed between storms is entrained by the increasing velocities during the rising limb, leaving less sediment supplied to the flow during the falling limb (Knighton 1998).

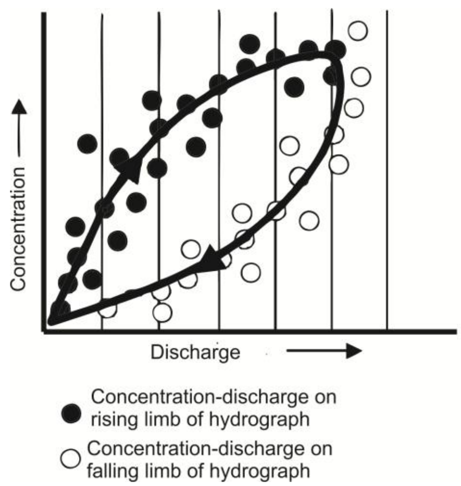

Figure 7. Generalized hysteresis curve for suspended sediment concentrations showing the rising limb of the hydrograph with higher concentrations than the falling limb.

Generally, the suspended sediment concentration increases with discharge (Figure 8) in the form of the empirical relationship:

$$C_o = kQ^b$$

Where: k and b are constants (Robert 2003). However, discharge is not a direct control on suspended sediment concentration but instead provides a surrogate for the turbulent forces suspending the sediment. As was mentioned above, the supply of suspended sediment is highly variable, leading to considerable scatter on plots of suspended sediment concentration and discharge, as seen in Figure 8.

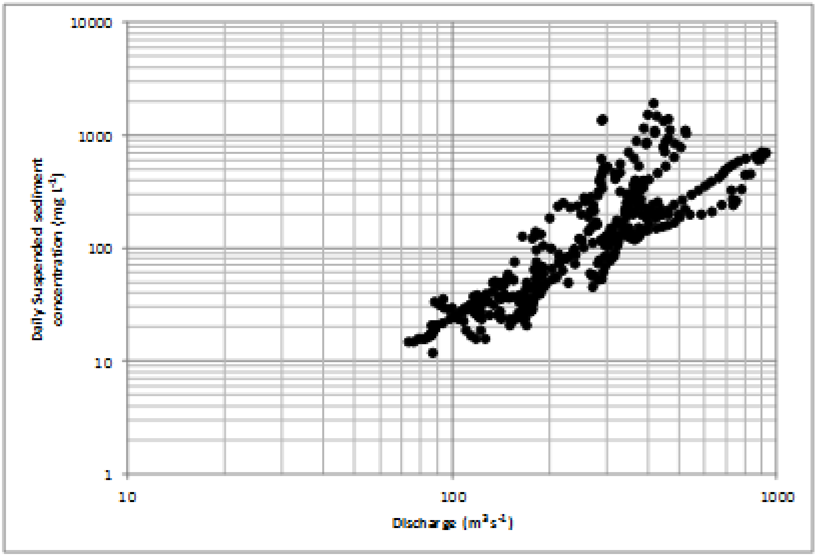

Figure 8. Relationship between suspended sediment concentration and discharge for the Mackenzie River East Channel at Inuvik (Data from the years 1975 – 1977 and 1994 for WSC 10LC002; k = 0.0075 and b = 1.7441).

The suspended sediment yield is the total suspended sediment output from a river basin over a given time period (Church et al. 1989; Knighton 1998; Church et al. 1999). Sediment yield is controlled by all of the factors that produce sediment over the landscape. Prediction of sediment yield may therefore provide a measure of the background level of suspended sediment supplied to a site.

Suspended sediment yield can be predicted using a sediment yield curve. Sediment yield curves plot sediment yield against drainage basin area; they have been developed for large regions of Canada (Church et al. 1999), including the Peace-Mackenzie region (Figure 9). Suspended sediment yield curves have the form:

$$\frac{L_d}{A_d} = k_s\, A_d{}^b$$

Where; L_d/A_d is the unit-area sediment yield, L_d is the average sediment load for the integral period of analysis (usually 1 year), A_d is the contributing drainage area, *b* is the scale exponent (also called specific yield) and *k*s is the true regional unit-area yield. For the Peace-Mackenzie region, Church et al. (1999) found the sediment yield ranged from 0.0094 to 0.016 mg km^{-2} yr^{-1}, k_s was -1.9 ± 0.057 and b was + 0.443 ± 0.017. In mountainous regions with recent glaciations such as British Colombia or the Peace-Mackenzie, specific sediment yield (sediment yield per unit area) was found to increase with drainage basin area (Church et al. 1989; Church et al. 1999).

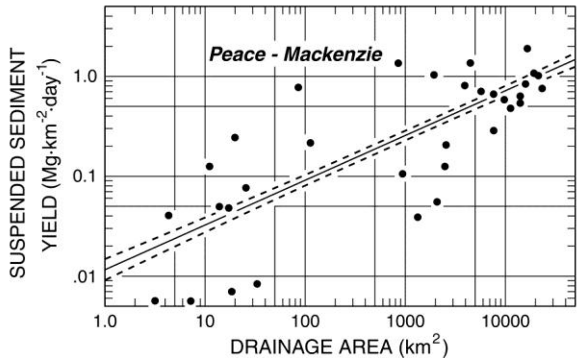

Figure 9. The regional suspended sediment yield curve for the Peace – Mackenzie region [from Church, et al. (1999)].

What is most useful is a prediction of the amount of sediment deposited on the bed given a set of conditions. A commonly used expression to predict the mass sediment deposition rate (Ψ) when only one size class is considered is:

$$\Psi = \frac{d\bar{C}}{dt} = \frac{w_s\bar{C}}{d}\left(1 - \frac{\tau_o}{\tau_{cd}}\right); \tau_o > \tau_{cd}$$

Where: $\bar{C}$ is the depth-averaged suspended sediment concentration, d is water depth, w_s is a constant related to the free settling velocity, τ_o is the bed shear stress and τ_{cd} is the critical shear stress for deposition (Mehta and McAnally 2007).

A related relationship was developed for fine sediment deposition using a recirculating flume (Krishnappan and Marsalek 2002). The models predict the fraction of the sediment deposited on the bed (f_d) for a given bed shear stress (τ_o) and grain size, related to the critical shear stress for deposition (τ_{cd}). The mathematical form of the deposition function is given below:

$f_d = 1.0 - 0.325\,(\frac{\tau_o}{\tau_{cd}} - 1)^{0.469}$ for $\{1 < \tau_o/\tau_{cd} < 12\}$

$f_d = 1.0$ for $\{\tau_o/\tau_{cd} < 1\}$

$f_d = 0$ for $\{\tau_o/\tau_{cd} > 12\}$

When the bed shear stress is much greater than the critical shear stress for deposition (τ_o/τ_{cd} >12) no deposition occurs; when the critical shear stress is greater than the bed shear stress all the sediment is deposited; when the ratio (τ_o/τ_{cd}) is between 1 and 12, part of the suspended sediment is deposited (Krishnappan and Marsalek 2002). The critical shear stress for deposition is related to the grain size of the material in suspension. Therefore, the size of the sediment that is supplied to the channel is critical in understanding the fate of sediment entering the system.

SUMMARY

Suspended load is carried within the water column. Suspended sediment concentrations are generally several orders of magnitude below their transport capacity and are therefore supply limited (Knighton 1998). Sediment remains in suspension as long as the upward motion of turbulent eddies are greater than the fall velocity of the sediment (Church 2006). The concentration of suspended sediment can be related to discharge, but considerable scatter is present in the relationship. Suspended sediment yield may be estimated using regional yield curves. Deposition of suspended sediment can be predicted using a relationship between shear stress and critical shear stress for deposition. Important variables that are related to concentrations and the deposition of suspended sediment are discharge, velocity, fall velocity of sediment, shear stress, critical shear stress for deposition and drainage basin area.

ESTIMATE SEDIMENTATION TRANSPORT CAPACITY AND CHANNEL PATTERNS

The previous sections discussed the forwarded method for understanding sedimentation and sediment transport processes. This section examines the inverse method, using the channel pattern, which is a product of sedimentation and deposition over a number of years, to understand transport capacity (Church 2006). Channel patterns in rivers form through the entrainment, transport and deposition of sediment (Burge and Guthrie 2013). River patterns therefore provide information about the underlying channel forming processes, including sediment input and sediment transport. In nature, a continuum of river patterns exists where patterns grade from one to another with changing boundary conditions, often downstream (Nanson and Knighton 1996). A discussion of different types of channel patterns and their characteristics and formative mechanisms follows.

The dominant sediment transport mode controls the nature of sedimentation (Church 2006). Schumm (1963) classified river channels into bedload, suspended load and mixed load. Bedload channels are dominated by sediment transported on the channel bed. Bedload dominated channels display gravel bars which flow diverges around, creating wider, shallower zones. In suspended load dominated systems, finer, more cohesive sediments are deposited over the floodplain during floods and strengthen stream banks, causing narrower and deeper channels. Mixed load dominated channels experience both modes of sedimentation.

The characteristics of suspended load, mixed load and bedload dominated channels were expanded upon by Church (2006). Table 2 describes several common channel patterns, along with their sediment transport regime, dominant sediment grain size, channel stability, and Shields number. The type of system (bedload, suspended load, or mixed load) can be delineated based on the Shields stress and the Reynolds number (Figure 10). Jammed channels have low Shields numbers and the bed is very stable. Threshold channels have moderate Shields numbers and the bed sediment is transported at near bankfull flows. Labile channels have high Shields numbers and the bed sediment is transported at all discharges.

Table 2. Classification of channel type based on Shields number and sediment transport regime (from Church 2006).

Channel morphology	Sediment transport regime	Dominant sediment grain size	Channel stability	Type/characteristic Shields number (channel forming)
Step-pools or boulder cascades; width typically a low multiple of largest boulder size; S > 3°	**Bed load dominated**; low total transport, but subject to debris flow	Cobble- or boulder-gravel	Stable for long periods with throughput of bed load finer than structure-forming clasts; subject to catastrophic destabilization in debris flows	Jammed channel 0.04+
Cobble-gravel channel bed; single thread or wandering; highly structured bed; relatively steep; low sinuosity; w/d > 20, except in headwater boulder channels	**Bed load dominated**; low total transport in partial transport regime; bed load may actually be less than 10% of total load	Cobble-gravel	Relatively stable for extended periods, but subject to major floods causing lateral channel instability and avulsion; may exhibit serially reoccupied secondary channels	Threshold channel 0.04+
Gravel to sandy-gravel; single thread to braided; limited, local bed structure; complex bar development by lateral accretion; moderately steep; low sinuosity; w/d very high (> 40)	**Bed load dominated**, but possibly high suspension load; partial transport to full mobility; bed load typically 1%–10% of total Load	Sandy-gravel to cobble-gravel	Subject to avulsion and frequent channel shifting; braid-form channels may be highly unstable, both laterally and vertically; single-thread channels subject to chute cutoffs a bends; deep scour possible at sharp bends	Threshold channel up to 0.15
Mainly single-thread, irregularly sinuous to meandered; lateral/point bar development by lateral and vertical accretion; levees present; moderate gradient; sinuosity < 2; w/d < 40	**Mixed load**; high proportion moves in suspension; full mobility with sandy bedforms	Sand to fine-gravel	Single-thread channels, irregular lateral instability or progressive meanders; braided channels laterally unstable; degrading channels exhibit both scour and channel widening	Transitional channel 0.15–1.0
Single thread, meandered with point bar development; significant levees; low gradient; sinuosity > 1.5; w/d < 20; serpentine meanders with cutoffs	**Suspension dominated** with sandy bedforms, but possibly significant bed load moving in the bedforms	Sandy channel bed, fine-sand to silt banks	Single-thread, highly sinuous channel; loop progression and extension with cutoffs; anastomosis possible, islands are defended by vegetation; vertical accretion in the floodplain; vertical degradation in channel	Labile channel > 1.0
Single-thread or anastomosed channels; prominent levees; very low gradient; sinuosity > 1.5; w/d < 15 in individual channels	**Suspension dominated**; minor bedform development; minor bed load	Silt to sandy channel bed, silty to clay-silt banks	Single-thread or anastomosed channels; common in deltas and inland basins; extensive wetlands and floodplain lakes; vertical accretion in floodplain; slow or no lateral movement of individual channels	Labile channel up to 10

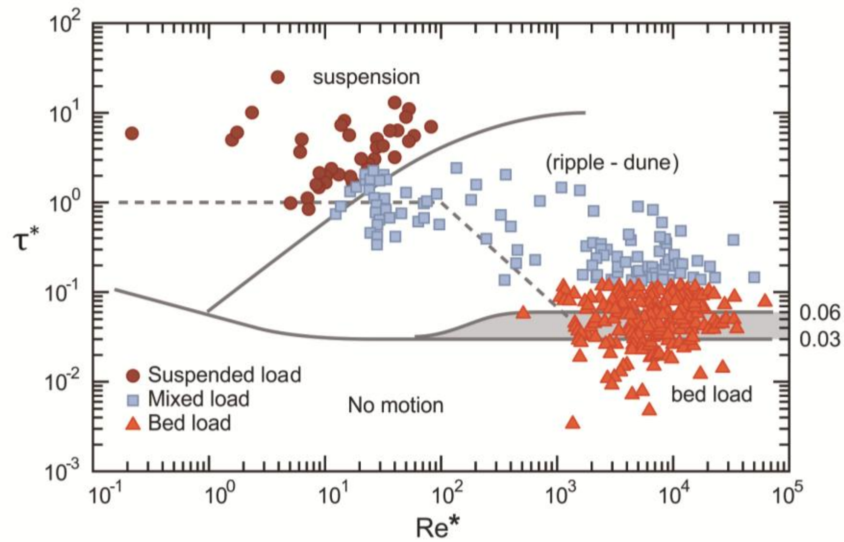

Figure 10. Shields stress and Reynolds number (Re∗ = μ^*D/ν, where μ^* is the shear velocity, v is the kinematic viscosity of water, and D is grain size) in suspended load, mixed load, and bedload streams (from Church 2006).

RIVER CLASSIFICATION

River pattern type can provide information on the processes occurring within channels. Several stream classification systems are used today (Leopold and Wolman 1957; Church 1992; Rosgen 1996). Figure 11 displays a classification system presented in Church (2006) (which was modified from Mollard 1973, Schumm 1985, and Church 1992). Sediment grain size (caliber) and slope are related on the Y-axis, while sediment supply is on the X-axis. From this diagram we can infer the relative size and volume of sediment input based on the channel pattern. Assessing the river type provides information about the current channel condition and provides constraints on expected future conditions.

The discussion of channel patterns begins with channel bed features common in upstream, headwater channels and is followed by patterns commonly occurring downstream. Channel bed features may be classified according to size as micro-form, meso-form, macro-form, and mega-form (Figure 12) (Hassan et al. 2008). Meso-form features, including cascade, step-pool, cascade-pool, plane-bed, riffle-pool, and dune-ripple, are the common channel archetypes discussed below.

Table 3 describes several important features of each reach type and provides a ranking of the susceptibility of the reach type to sedimentation due to sediment input. The following discussion introduces channel bed patterns and their characteristics.

Occurring in headwater streams, colluvial channels usually contain a thin layer of alluvium within or overlying valley fill colluvium that is formed during weak ephemeral fluvial transport (Montgomery and Buffington 1997).

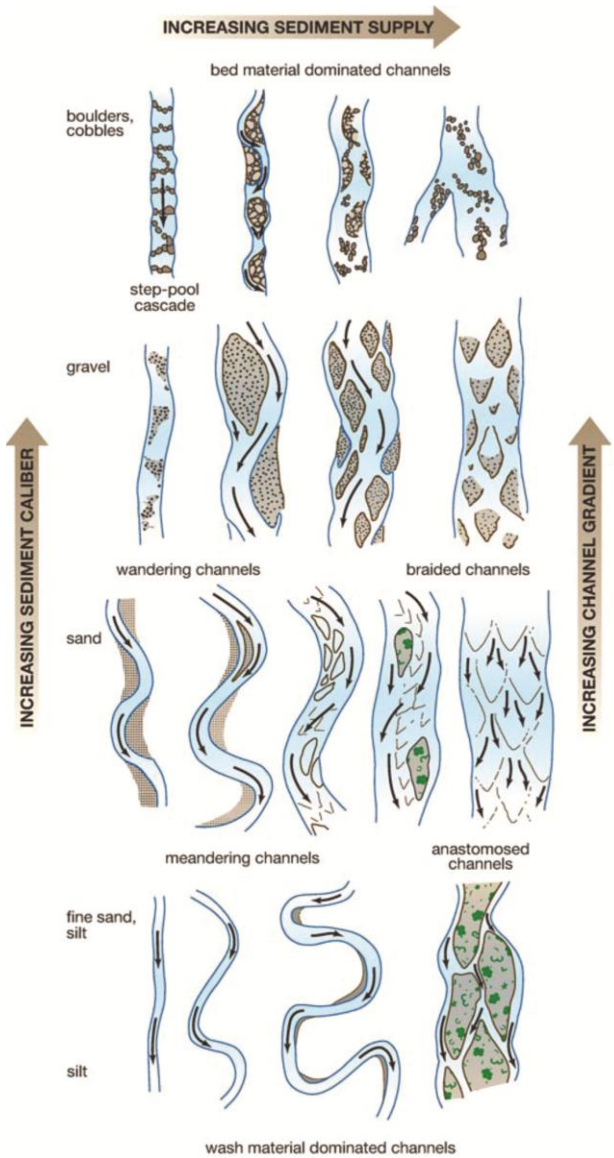

Figure 11. Channel patterns in relation to grain size, gradient, and sediment input (from Church 2006, modified from Mollard 1973, Schumm 1985, and Church 1992).

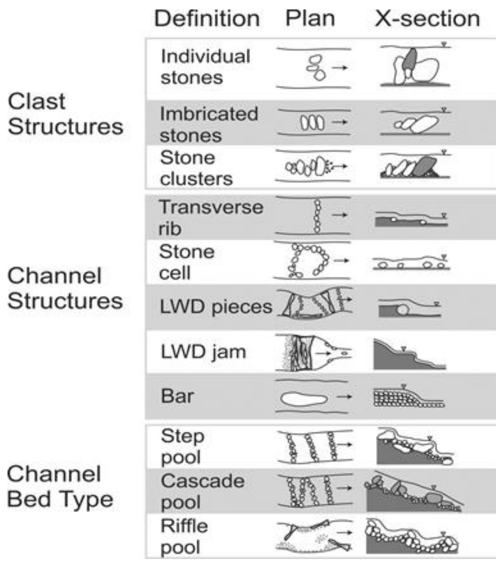

Figure 12. Channel elements at the micro- to meso-scale (Hassan et al. 2008).

Table 3. Diagnostic features of channel bed morphology types (modified from Montgomery and Buffington 1997).

	Dune-ripple	Pool-riffle	Plane-bed	Step-pool	Cascade	Cascade-pool	Bedrock	Colluvial
Sedimentation susceptibility	High	Moderate	Moderate / Low depending on armouring	Low	Low	Low	Low	Low
Typical bed material	Sand	Gravel	Gravel-cobble	Cobble-boulder	Boulder	Boulder	Rock	Variable
Bedform pattern	Multi-layered	Laterally oscillatory	Featureless	Vertically oscillatory	Random	Random with pools	Irregular	Variable
Dominant roughness elements	Sinuosity, bedforms (dunes, ripples, bars) grains, banks	Barforms (bars, pools), grains, sinuosity, banks	Grains, banks	Bedforms (steps, pools) grains, banks	Grains, banks	Grains, banks	Boundary (bed and banks)	Grains
Dominant sediment sources	Fluvial bank failure	Fluvial bank failure	Fluvial bank failure, debris flows	Fluvial hillslope, debris flows	Fluvial hillslope, debris flows	Fluvial hillslope, debris flows	Fluvial hillslope, debris flows	Hillslope, debris flows
Sediment storage elements	Overbank, bedforms	Overbank, bedforms	Overbank	Bedforms	Lee and stoss sides of flow obstructions	Lee and stoss sides of flow obstructions	Pockets	Bed
Typical confinement	Unconfined	Unconfined	Variable	Confined	Confined	Confined	Confined	Confined
Typical pools spacing (channel widths)	5 to 7	5 to 7	none	1 to 4	<1	<1	Variable	Unknown

River channels exhibit a braided pattern where flow dissects mid-channel bars at flows lower than the bankfull level (Ashmore 1991; Smith 1976). Specific stream power in gravel braided rivers ranges between 120 and 300 Wm^{-2} (Ferguson 1981). At low flows braided rivers are braided in appearance, but they may only display a single channel when bars are submerged at high flows. The channel bed and location of channels within braided rivers are unstable (Ashmore 1991). They may have gravel or sand beds, high width-depth ratios, and the highest slope and energy levels (stream power) of all alluvial river types (Smith and Putnam 1980; Ferguson 1981; Ashmore 1991). Braided rivers may also display low bank strength (Eaton et al. 2010). Due to the high energy conditions, slopes, and velocities, braided channels are generally not susceptible to bed sedimentation. If sedimentation occurs it will not change the pattern because the channel is already overloaded with sediment.

Anabranching describes river channels that divide and rejoin downstream (Nanson and Knighton 1996). Two of the most common anabranching channel patterns in Canada, defined by flow around permanent or semi-permanent islands, are anastomosed and wandering (Nanson and Knighton 1996). The wandering pattern describes a transitional pattern between braided and meandering, with ephemeral or perennial anabranches around semi-permanent islands connected by single channel reaches (Neill 1973; Church 1983; Desloges and Church 1989; Burge 2005). Anastomosed is reserved for a type of river with multiple, interconnected, coexisting channels on alluvial plains (Smith and Putnam 1980; Makaske 2001). Anastomosed rivers have high aggradation rates and low slopes (Nanson and Knighton 1996; Makaske 2001; Makaske et al. 2002; Smith 1983), while wandering rivers haves slopes between braided and meandering channels (Burge 2005; Desloges and Church 1989) and are thought to be in grade (Church 1983; Desloges and Church 1989). For example, the anastomosed Columbia River was found to aggrade at a rate of 1.75 mm/yr (Makaske et al. 2002), while the wandering Bella Coola River shows evidence of being vertically stable for some time (Church 1983; Desloges and Church 1989). Wandering and anastomosed channels change location quickly through avulsion. Sediment transport conditions are driven by the energy level within the channel system, which varies from high energy braided (Leopold and Wolman 1957) to very low energy anastomosed (Smith and Putnam 1980; Makaske 2001). Due to the moderate energy conditions, slopes, and velocities, wandering channels may be susceptible to bed sedimentation. In contrast, anastomosed channels have low energy conditions and are susceptible to sedimentation.

Meandering channels generally display higher energy conditions than anastomosed systems (van den Berg 1995). Alluvial meanders migrate laterally in the channels they shape in their own deposits (Twidale 2004). Channels migrate as banks erode on the outside of channel bends and deposition occurs on the inside of channel bends. Channel depth varies downstream with regular alteration between pools and shoals, bars or riffles (Twidale 2004) but generally, the more sinuous a stream the deeper the pools. As meander channels migrate laterally they may intersect, creating a cutoff and an oxbow lake. Channel migration rates are related to the radius of curvature of the meander bend (Nanson and Hickin 1986). Meandering channels generally have strong banks (Eaton et al. 2010). Due to the moderate energy conditions, meandering channels are generally susceptible to bed sedimentation.

The development of structured streambeds such as step-pools or boulder cascades depends on the maintenance of low sediment transport rates (Church 2006) created by low sediment inputs. The structure of the streambed is formed by large clasts that seldom move (Chin 1989), and by keystones that other large clasts jam upon (Zimmerman and Church 2001). These structures persist in time and their maintenance is related to the entrapment of particles in the high roughness area of the bed (Lamarre and Roy 2008a). Step-pool or boulder cascade channels normally transport far less sediment than the theoretical maximum (Church 2006), and mobile sediment is typically finer than the material exposed on the bed surface.

Cascade and cascade-pool channels are characterized by longitudinally and laterally disorganized bed materials that are typically composed of cobbles and boulders (Montgomery and Buffington 1997). Occurring on steep slopes confined by valley sides, cascade channels dissipate energy through high velocity jets and low velocity wakes occurring around individual clasts. Small pools are common, occurring less than one channel width apart, but do not span the channel. The largest bed material is immobile due to large particle sizes that are transported only during large and infrequent (50-100 years) events or debris flows and floods. Due to the high turbulence levels, velocities and transport capacity, cascade and cascade-pool channels are generally not susceptible to bed sedimentation.

Step-pool channels are characterized by large steps that span the channel and are composed of large casts that separate pools containing finer material downstream (Table 3) (Ashida et al. 1976; Griffiths 1980; Whittaker and Jaeggi 1982; Whittaker 1987; Chin 1989; Grant et al. 1990; Burge and Corbett 2007). Steps in the bed cause the primary flow and the channel bed to oscillate vertically downstream, which results in an alternation between critical to super critical flow downstream (Bowman 1977; Chin 1989; Zimmerman and Church 2001). The spacing between steps is between one to four channel widths and steps provide much of the elevation drop and roughness in step-pool channels (Ashida et al. 1976; Whittaker and Jaeggi 1982; Whittaker 1987; Chin 1989). Step-pool channels develop on steep gradients, have small width-to-depth ratios and are generally confined by valley sides. As with cascade systems, steps are only mobile during large and infrequent flows while finer material travels as bedload at lower more frequent flows over steps (Whittaker 1987; Chin 1989; Grant et al. 1990; Ashida et al. 1981). Travel distance by clasts at low to moderate flows seems to be related to excess stream power (ω_o-ω_c) (Lamarre and Roy 2008b). Due to the high turbulence levels, velocities and transport capacity, step-pool channels are generally not susceptible to bed sedimentation

Riffle-pool channels have an undulating bed that defines a sequence of bars, pools, and riffles (Table 3). Pools are topographic low points within the channel downstream while riffles are topographic high points. Riffle-pool morphology occurs naturally in the environment or can be forced by either large woody debris (MacVicar and Roy 2007) or bedrock outcrops that impinge the flow (Thompson 2007). Pools are spaced between five to seven channel widths apart (Leopold et al. 1964; Keller and Melhorn 1978). Riffle-pool channels occur at moderate to low gradients and are generally unconfined with well-developed floodplains. Substrate in riffle-pool streams varies from sand to cobble, but gravel is typical (Montgomery and Buffington 1997). Riffle-pool channels have heterogeneous beds with coarser sediment present in riffles and finer sediment in pools. The topographical variability in these systems creates contraction and expansion of the flow that leads to acceleration and deceleration of the flow, respectively (MacVicar and Roy 2007). Full sediment mobility is observed in the pool tail where flow accelerates and the bed shear stresses are higher (MacVicar and Roy 2011). Decelerated flow at pool entrances is characterized by higher turbulence (Kironoto and Graf 1995; MacVicar and Roy 2007). Due to the moderate slopes, velocities, and transport capacity, riffle-pool channels are generally moderately susceptible to bed sedimentation, particularly within pools or riffles with low angles at low flows.

Plane-bed channels differ from step-pool channels and riffle-pool channels in that they lack rhythmic bedforms and are instead characterized by long stretches of relatively featureless bed (Table 3) (Montgomery and Buffington 1997). They also lack discrete bars, and have large values of relative roughness (High D_{90}/depth). Plane-bed channels commonly exhibit armoured surfaces that are only mobile at near bankfull discharge (sediment is supply limited). Unarmoured surfaces indicate a balance between transport capacity and sediment supply (Dietrich et al. 1989). Unarmoured beds are generally more susceptible to sedimentation than armoured beds.

Dune-ripple channels are low-gradient sand-bed channels that contain ripples, wave forms, and other bedload morphologies (Table 3) (Montgomery and Buffington 1997). Several scales of bedforms may develop with ripples, bedload sheets, and small dunes that may climb over more mobile dunes (Montgomery and Buffington 1997). The frequency of bed mobility and the presence of ripples and/or dunes distinguish dune-ripple channels from riffle-pool channels. The bedform configuration of dune-ripple channels depends on flow depth, velocity, bed surface grain size, and sediment transport rate, and follows a well-known sequence of bedforms with increasing flow depth and velocity (Montgomery and Buffington 1997; Gilbert and Murphy 1914; Simons et al. 1965). In contrast to the low sediment transport regime of plane bed and riffle-pool systems, dune-ripple channels exhibit live bed transport, in which sediment transport occurs at all stages. Due to the low gradient and low transport capacity, dune-ripple channels are generally susceptible to bed sedimentation.

BED SEDIMENTATION

The following section provides a short discussion on the effects of excess sediment supplied to channels. Stream bed features provide evidence of the background sediment supply. Changes in sediment supply can cause aggradation or degradation. When sediment is introduced to transport-limited channels they may aggrade because they cannot transport the sediment that is supplied to the reach. These channel beds may become overwhelmed with sediment and bar forms will cover larger bed areas (Hassan et al. 2008). Supply-limited channels may remain stable when sediment is supplied to the reach because channels can transport more sediment out of the reach than is supplied to a reach, a condition that would normally cause degradation. The beds of channels that are degrading contain large cobbles or boulders that are exposed as the smaller particles are removed from the reach. There is also a lack of mobile sediment within the reach.

Generally, coarse sediment that is supplied to the channel is deposited locally on the channel bed. This deposition can be in the form of sheets or waves of gravel but is often in the form of in-channel bars.

Figure 13 shows the effect of increasing sediment supply into a reach for three different reach types that were described in the previous section. Where sediment input overwhelms the channel, such as during a landslide or debris flow, coarse sediment may be deposited on the floodplain as well as the channel. Deposition that overwhelms the channel often results in a change in river pattern, from meandering to braiding for example.

On a macro scale, sedimentation can occur as a wave that may or may not propagate downstream (James 2006). In many parts of the world, episodic sediment inputs above background levels caused by deforestation, intensive agriculture, mining, fire, road building, or urbanization have resulted in channel aggradation or floodplain burial (James 2006). Sediment waves propagate downstream through translation or dispersion (Lisle et al. 2001). During translation the bed elevation increases then decreases as the wave moves past a cross section. During dispersion the sediment wave flattens out and disperses *in situ*.

Sediment waves may store sediment for long periods. An example of this is the sedimentation caused by hydraulic mining in California in the late 19^{th} century (Gilbert 1917; James 2006). In Redwood Creek, CA, large inputs of sediment from landslides, gullies and bank erosion caused aggradation of several metres during 20- to 50-year return period floods that were subsequently incised through (Madej et al. 2009). The effects of channel aggradation have persisted for >40 years (Madej et al. 2009).

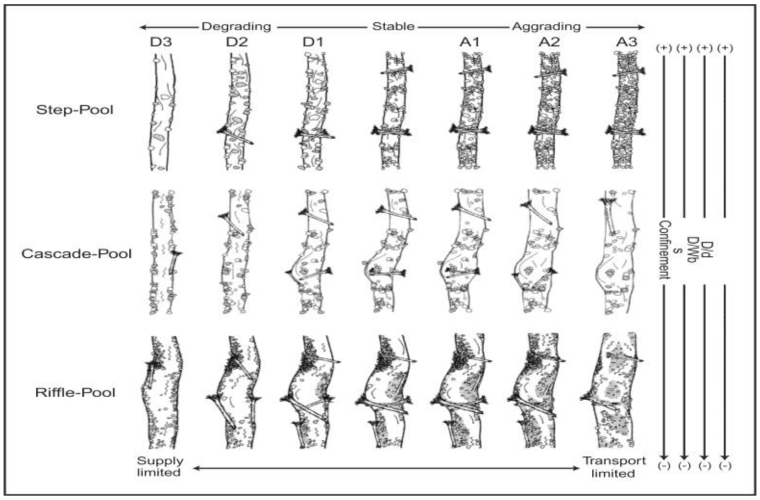

Figure 13. Channel morphology matrix showing effects of increasing sediment input on step-pool, cascade pool, and riffle pool channels (British Columbia Ministry of Forest and British Columbia Ministry of Environment 1996).

A methodology developed to investigate areas susceptible to sedimentation is “sediment routing” (Benda and Dunne 1997; Jacobson and Gran 1999). These models predict locations of sedimentation within a drainage basin. Benda and Dunne (1997) used a stochastic model of sediment transfer and storage in a channel network to route sediment. Sediment supply into the channel network was unsteady and non-uniform thus creating sediment waves or aggradation. Jacobson and Gran (1999) used a simple model based on a GIS network to account for the arrival of what they called gravel “packets” at locations along the channel. Both models predict zones of sedimentation within the drainage. Benda and Dunne (1997) found that;

- small channels in the upper portion of a basin have a low probability of aggradation,
- medium size channels in the middle of a basin have a higher probability of aggradation because there are more incoming channels and landslides, and
- large channels in the lower portion of a basin have a lower aggradation probability.

Fine sediment supplied to the channel may deposit on riffles or within pools depending on the conditions at the specific location. Fine sediment deposition often results in an increase in the embeddedness of the sediment (Waters 1995). Embeddedness refers to the amount of fine sediment that surrounds coarse sediment on the channel bed. An experiment on Carnation Creek in British Columbia showed that fine sediment (0.5-2.0 mm) may rapidly deposit at low flows on riffles with low shear stress values, thereby increasing embeddedness, but be rapidly transported out of riffles with higher shear stress values (Culp et al. 1986). During low flows, fine sediment supplied to the channel may therefore be deposited in riffles or pools.

SUMMARY

The inverse method may be used to illustrate the antecedent conditions within a stream channel by providing information about the hydraulic and sediment transport conditions that lead to the present channel pattern. A number of channel patterns were discussed and their susceptibility to bed sedimentation was estimated. The preceding sections described methods used to understand sediment transport, sedimentation, and their effects on river channels. Even given this limited overview, one can see that the study of sediment transport is a complex science, with many interrelated variables. However, it is also sufficiently mature and the variables are understood well enough to distinguish order of magnitude effects. The next section outlines research into the effects of pipeline construction on downstream sedimentation.

SEDIMENTATION RELATED TO PIPELINE CONSTRUCTION

Pipeline construction can produce sedimentation downstream, and different construction techniques produce different volumes of sediment for sedimentation. Table 4 displays the potential for the generation of suspended sediment from different trenching techniques. Reid and Anderson (1999) reviewed studies examining the effects of open-cut pipeline water crossings over a 25 year period. The summary of their findings is presented in Table 5. Most studies indicate that sediment released during construction can cause short-term (1-2 year) changes to stream aquatic life and their habitats. Specific identified effects include;

- alterations to stream bed conditions,
- reductions in the abundance and diversity of benthic invertebrate communities, and
- reductions in the abundance of fish populations.

The effects were typically not residual and systems normally recovered to post-construction conditions within one year.

Table 4. Potential for suspended sediment generation associated with different open-cut trenching techniques (from Reid and Anderson 1999).

Crossing Method	Level of Sediment Generation	Applicability
Backhoe	Substantial levels of turbidity can be generated during trenching and backfilling. As the technique is fast, the duration of sedimentation can be limited	Appropriate for all widths of shallow streams (< 1 m). Can be adapted for crossings of greater depth. Best applied when sediment concerns are low or when minimizing the duration of construction is seen as the best mitigation measure.
Plough	Generation of turbidity mainly limited to grading of stream banks	Shallow watercourses (< 1 m) with little or no flow and soft substrates.
Dragline (Yo-Yo)	Method is slow, requiring numerous passes with the bucket resulting in long periods of elevated sediment load	Appropriate for moderately deep (< 10 m and wide (> 20 m) water courses with soft substrates.
Dredge	Sedimentation is limited when dredge is used and instream storage of spoil is not required. Concern regarding proper settling of dredged slurry before discharge.	Appropriate for large, deep watercourse with soft substrate.
Bucket Wheel Trencher	Crossings can be quickly excavated and therefore the duration of sedimentation is limited. Since spoil is stored instream, high sediment loads may result.	Shallow (< 1 m) water courses with firm fine grained substrates (no cobbles or bedrock) and streamflow is very low or absent.

Table 5. Summary of studies monitoring the effects of open-cut pipeline water crossings (modified from Reid and Anderson 1999).

Location	Turbidity or Suspended sediment levels during construction	Duration of constructi on	Immediate effects	Long term effects
Findlay Creek, Ontario	40-2960 mg/L	4 days	**Sedimentological Effects:** Up to 0.3 m of sand deposited within 100m downstream of crossing. Deposited sand moved as a dune downstream altering channel morphology. **Ecological Effects:** Reduction in benthic invertebrate species diversity and brook trout abundance and increased invertebrate drift during construction.	**After one year:** **Sediment Deposition:** Deposited sediment flushed out **Ecological Effects**: Recovery of benthic invertebrate and fish community.
Unnamed stream, Ontario	396.6 JTU	n/a	**Sedimentological Effects:** 0.25 m mean depth. **Ecological effects:** Significantly lower downstream invertebrate abundance	**After one year:** **Sediment Deposition:** No trace of silt deposits **Ecological Effects**: Benthic invertebrates recovered
Four streams, New York	<1-11 000 mg/L	1-3 days	**Sedimentological Effects:** Increase in gravel and cobble material and a reduction in fines in riffle habitats at the crossing	**After two years:** Reduction in the amount of instream cover (pools, rocks, woody debris and submerged vegetation. After two-four years: No statistical difference in the diversity of benthic invertebrate or fish communities **After four years:** Two of the four crossings had instream cover comparable to pre-construction.
Eight crossings of the Moyie River, Idaho	189-3235 mg/L	>30 days	**Sedimentological Effects:** Increased embeddedness of the river bed **Ecological Effects:** Non-significant reductions in benthic invertebrate abundance and diversity	**After one month:** Embeddedness returned to preconstruction levels following spring freshet. Benthic invertebrates recovered
Fletcher Creek, Michigan	4312 mg/L 2502 mg/L	1 day	**Sedimentological Effects:** Increased sediment deposition within 50 m downstream.	n/a
Boardman River, Michigan	189-732 mg/L 236-189 mg/L	1 day	**Sedimentological Effects:** Increased sediment deposition within 50 m downstream.	**After 1.5 months:** Sediment flushed from bed
Hodgson Creek, North West Territories	Avg. TSS > 300 mg/L	14 days	**Sedimentological Effects:** Increased downstream sediment deposition. **Ecological Effects:** Increased invertebrate drift during construction. No measurable effect on overwintering fish.	**After one year:** Sediment removed during spring freshet. No effect on standing crop, species richness, and functional group composition of benthic invertebrate community

Location	Turbidity or Suspended sediment levels during construction	Duration of constructi on	Immediate effects	Long term effects
Bow River, Alberta	0.4-576 mg/L	14 days	**Sedimentological Effects:** Increased downstream sediment deposition **Ecological Effects:** Viable mountain whitefish eggs found in downstream riffle habitat	n/a
Red Deer, River, Alberta	4.0-132 mg/L	14 days	**Sedimentological Effects:** Increased downstream sediment deposition **Ecological Effects:** Decrease in benthic invertebrate density and diversity	n/a
Two Caribou River Tributaries, Manitoba	100-250 mg/L 10-740 mg/L	3 hours 1.25 hours	**Sedimentological Effects:** Increased sediment deposition within 100 m of crossing. **Ecological Effects:** No change in benthic invertebrate community. Qualitative reduction in downstream abundance of arctic grayling fry.	n/a
Little Miami River, Ohio	25-1461 mg/L 35-359 mg/L	2 days	**Sedimentological Effects:** Increased fines in the stream bed up to 200 m downstream of crossing. Increased sediment bedload for several weeks. **Ecological Effects:** Decrease in density and diversity of benthic invertebrates. Reduction in downstream fish abundance.	**After one year:** Fines flushed from the stream bed by high flows during winter and early spring. **After eight months:** Fish and invertebrate communities back to pre-construction levels
Archibald Creek, British Columbia	456-10660 mg/L	2 days	**Sedimentological Effects:** Increased deposition of silt and sand (<2 mm) 75 m downstream of crossing. Statistically insignificant reduction in benthic invertebrate diversity. Reduction in benthic invertebrate abundance.	**After two years:** Deposited sediment removed **After one year:** Benthic invertebrate community fully recovered
Falling Creek, Florida	3-151 NTU	14-21 days	**Sedimentological Effects:** No sediment deposition observed **Ecological Effects:** No change in benthic invertebrate community observed	n/a
Canada Creek, Michigan	90-380 mg/L Initial peak: 1105 mg/L	1.75 hours	**Sedimentological Effects:** No change in stream bed composition. **Ecological Effects:** During ramp excavation, short term increase in invertebrate drift. No change in benthic invertebrate or fish communities.	n/a
Fort Nelson River, British Columbia	25-140 mg/L	n/a	**Ecological Effects:** Increase in invertebrate drift during construction	n/a

Location	Turbidity or Suspended sediment levels during construction	Duration of construction	Immediate effects	Long term effects
Bushkill Creek, Pennsylvania	n/a	n/a	**Ecological Effects:** Short term (30 day) increase in the abundance and species diversity of benthic invertebrates at the crossing	Long term increase in benthic invertebrate abundance and diversity at the crossing
Oakville Creek, Ontario	15-118 mg/L	6 days	**Ecological Effects:** Reduced downstream benthic invertebrate abundance within 100 m of crossing.	**After one year:** Recovery of benthic invertebrate community
Credit River, Ontario	41-776 NTU	3 days	**Ecological Effects:** Reduced downstream benthic invertebrate abundance and diversity.	**After one year:** Recovery of benthic invertebrate community
Bronte Creek, Ontario	34-50 mg/L	6 days	**Ecological Effects:** Reduced downstream benthic invertebrate abundance and diversity.	**After one year:** Recovery of benthic invertebrate community
Two crossings of the Moyie River, British Columbia	10-2680 mg/L	5-6 days	**Ecological Effects:** No increase in whitefish egg mortality.One month post construction, fewer juvenile whitefish downstream of one crossing but more downstream of the second.	n/a

Reid et al. (2004) developed a set of models to predict sediment total suspended solid (TSS) concentrations for three different types of pipeline construction methods (open-cut, dam and pump, and flumed) (Table 6).

Table 6. Models for predicting mean (C_{av}) and peak (C_p) TSS concentrations immediately downstream of pipeline water crossing construction (from Reid et al. 2004).

Construction activity	Parameter	Equation
All activities	Mean TSS	$C_{av} = 1.5x10^6 U^{1.09} D_{50}{}^{0.95} P_f{}^{2.35} q^{-1}$
	Peak TSS	$C_p = 5.7x10^5 U^{1.86} D_{50}{}^{0.57} P_f{}^{1.2} q^{-1}$
Trenching	Mean TSS	$C_{av} = 4.53x10^6 U\ D_{50}\ P_f{}^{2.77} q^{-1}$
	Peak TSS	$C_p = 1.05x10^6 U^{1.67} D_{50}{}^{0.67} P_f{}^{1.65} q^{-1}$
Pipe lowering	Mean TSS	$C_{av} = 3.84x10^5 U^{1.15} D_{50}{}^{0.93} P_f{}^{2.3} q^{-1}$
Back filling	Mean TSS	$C_{av} = 6.95x10^5 U^{1.54} D_{50}{}^{0.73} P_f{}^{2.44} q^{-1}$
	Peak TSS	$C_p = 4.95x10^6 U^{2.08} D_{50}{}^{0.46} P_f{}^{1.6} q^{-1}$

Where: U is the mean flow velocity during construction, P_f is the percentage fines of the excavated material, D_{50} is the median sediment particle size of the excavated material, and q is the unit discharge (Q/W).

They found that open cut crossings displayed the highest mean TSS concentrations during all phases of construction. Most of the dam and pump and 50% of the flumed crossings limited TSS concentrations to less than 25 mg L^{-1} above background levels (Reid et al. 2004).

SUMMARY

Elevated suspended sediment concentrations due to pipeline construction are generally short lived and local. A review of the effects of pipeline construction are summarised in Table 5. Sedimentation can be predicted using velocity, percentage fines, the median grain size, and unit discharge.

FATE OF INTRODUCED SEDIMENT TO NORTHERN CANADIAN RIVERS

Literature on the fate of sediment introduced to northern rivers is sparse. Several studies (e.g., Brunskill et al. 1973; Rosenberg and Snow 1975; Rosenberg and Wiens 1978) were conducted in the 1970s to investigate the effects of sedimentation due to the expansion of linear infrastructure such as roads and pipelines in the north. Some of the biological effects are listed in Table 7. Although not the focus, the fate of sediment introduced into northern rivers is discussed within several of these studies and is presented below. The section ends with a discussion of the importance of river ice in suspended sediment generation in northern rivers.

Table 7. Examples of effects of suspended sediments on northern river benthic invertebrates.

Location	Effects	Reference
n/a	Clear waters (< 20 mg/L of SS) had higher standing crops of benthic invertebrates than turbid waters (100-2000 mg/L of SS)	(Brunskill et al. 1973)
Headwater streams	Headwater streams carrying low concentrations of suspended sediment suffered greater reductions in benthic invertebrate standing crops when subjected to increased sediment loads than did more turbid waters downstream regions of the streams	(Brunskill et al. 1973)
Mackenzie delta lakes	Mackenzie delta lakes where clear had 41-91 times the standing crop and five times the number of taxa of benthic invertebrates than did turbid lakes	(Brunskill et al. 1973)
Mackenzie River tributaries and delta lakes	Mackenzie River tributaries and delta lakes show a great decrease in standing crop of zoobenthos above 10-15 mg/L.	(Brunskill et al. 1973)
Caribou Bar Creek	Mudslide caused a reduction of the standing crop of benthic invertebrates of 70%, upstream of the mudslide was 3.5 times higher than below. Standing crop of invertebrates recovered to levels above the slide after one month.	(Brunskill et al. 1973) (Rosenberg and and Snow 1975)

A mudslide occurring on Caribou Bar Creek, a tributary of the Porcupine River, Y.T., in mid-August 1972 provides an example of the effects of sediment input into a northern river (Figure 14). An estimated 2000-2600 metric tons of sediment was released during the initial slide and the slide was active intermittently through the 1973 open water season (Rosenberg and Snow 1975). The natural retrogressive-thaw flow to bi-modal flow land slide resulted in suspended sediment concentrations of 3.8 to 10.6 mg/L. A report by Rosenberg and Snow (1975) provides a great deal of detail into the effect of suspended sediment on invertebrates, but unfortunately it does not discuss the fate of the sediment once it entered the stream channel.

Figure 14. Natural retrogressive-thaw flow side on Caribou Bar Creek, Y.T. Slide occurred between August 13-15,1972. (from Rosenberg and Snow 1975).

On the Martin River, a tributary of the Mackenzie River, studies of highway crossings on the Mackenzie Valley watershed can provide insight into the fate of sediment in northern rivers. Sediment concentrations were monitored upstream and downstream of pools at six stations (Rosenberg and Snow 1975). Riffle shape was cited as a control on sediment deposition at two sites, where a wider (~30 m), shallower (~13 cm), and slower (~0.2 m/s) riffle had greater sediment deposition than a narrower (~10 m), deeper (~25 cm), and faster ~0.5 m/s) riffle. The wide riffle displayed a poorly sorted bed composition from silt to boulders, while the narrow riffle displayed mainly gravel bed sediments.

Located approximately 25 km southeast of Inuvik, Campbell Creek, NWT was the first major watershed crossed by the Dempster Highway. The watershed drains low relief taiga and tundra before flowing southwest into Campbell Lake. The crossing contains two 30 m long, 2.4 m diameter culverts that were installed across Campbell Creek during the winter of 1971-1972 (Rosenberg and Snow 1975). The road was not consolidated when the spring flooding occurred in early June 1972, causing considerable surface erosion. In the same year following the flood, the roadway was raised ~5.5 m above the culverts; however, floodwaters in 1973 overtopped the highway causing erosion of the surface and portions of the roadway itself (Rosenberg and Snow 1975). Fill areas had not stabilized by the spring of 1973, causing visible amounts of sediment to be introduced downstream of the crossing. The channel bed upstream of the crossing was composed of gravel with finer sediments, while downstream of the crossing a visibly silty layer covered the channel bed (Rosenberg and Snow 1975). The grain size distribution of the bed sediment above and below the crossing was analysed (Table 8). On average, the bed sediment downstream of the crossing had almost 8% higher fine sediment (silt and clay) than above the crossing. It should be noted that the bed of Campbell Creek displays very high levels of silt and clay, between 58 and 66%, and that one site containing gravel drove most of the difference observed in the average content of fines.

Table 8. Bed grain size characteristics of Campbell Creek in 1972 and 1973 following road construction [modified from Rosenberg and Snow (1975)].

Date	Upstream		Downstream		Difference	
	Coarse (> 0.05 mm)	Fine (< 0.05 mm)	Coarse (> 0.05 mm)	Fine (< 0.05 mm)	Coarse	Fine
17-Jul-72	-	-	23.41	73.20	-	-
11-Aug-72	-	-	53.71	44.00	-	-
19-Sep-72	62.29	32.80	31.58	58.00	-	-
24-Nov-72	-	-	34.23	57.00	-	-
25-Jun-73	14.81	57.19	-	-	-	-
27-Jun-73	32.13	59.20	18.95	59.60	-	-
27-Jun-73	-	-	10.17	80.00	-	-
20-Aug-73	16.03	76.00	11.78	80.00	-	-
20-Aug-73	26.04	67.20	8.51	79.20	-	-
Mean	***30.26***	***58.48***	***24.04***	***66.38***	***-6.22***	***7.90***
SEM	***8.63***	***7.23***	***5.43***	***4.79***	***-3.20***	***-2.43***

An experiential study into the effects of sediment input on benthic macro invertebrates was conducted on the Harris River, a riffle-pool, brown-water tributary of the Mackenzie River east of Fort Simpson. Silty-clay sediment was added to the river upstream of a riffle, to concentrations between 37 and 478 mg/L. Following the sediment addition, ~85% of the sediment added in each experiment settled to the stream bottom within the first 7.5 m and ~90% had settled by 15 m. Concentrations of 164 and 478 mg/L left noticeable deposits of sediment on the stream bottom. A subsequent study at the same location (Rosenberg and Wiens 1978) found macrobenthos drift increased slightly with increased suspended sediment concentrations.

RIVER ICE

An additional factor in northern rivers that has not been considered in the FRAT is the effect of river ice on suspended sediment concentrations. The following provides a short review of these effects. During a dynamic breakup, large snowmelt runoff encounters an intact ice cover that retains much of its winter thickness and strength (Prowse and Culp 2003). Downstream forces are great enough to break the intact ice sheet, driving it downstream (Prowse and Culp 2003). An accumulation of ice flows may develop into an ice jam as the energy of the breakup dissipates. The thickness and hydraulic roughness of the ice within the ice jam causes a backwater to develop, leading to overbank flooding. Northern rivers that experience frequent ice jams have hydraulic geometry relationships that might be different than ones observed in a temperate climate. Ice jams can cause wide channels with two floodplain levels (Boucher et al. 2009).

River ice jams can cause suspended sediment concentrations to spike, even at relatively low discharges (Prowse and Culp 2003; Prowse 1993). During breakup high velocities, high stages and the mechanical action of the ice itself work to erode river channels (Prowse and Culp 2003). Unlike under open water conditions, suspended sediment load cannot be estimated using a sediment load-discharge rating curve, particularly during the breakup phase (Milburn and Prowse 1996). Research on the Liard River, NWT (Prowse 1993) and the upper Saint John River in eastern Canada (Beltaos et al. 1994) displayed low background suspended sediment concentrations (<10 mg/L) prior to breakup, which increased by an order of magnitude (100s of mg/L) prior to breakup and reached up to >1000mg/L during breakup surges, several times open water levels. However, it remains difficult to estimate suspended load during breakup (Prowse and Culp, 2003). For example, in one Alaska river, the greatest suspended sediment concentration occurs during the dynamic breakup and ~ 75% of the annual sediment load is transported within 3-4 weeks of breakup (Walker 1969).

SUMMARY

The previous sections provided a review of processes involved in the transport and deposition of river sediment. There are two ways to investigate sediment transport and sedimentation: a forward physical approach or an inverse morphological approach. The forward approach uses known physics to predict sediment transport and sedimentation. The inverse approach uses the observed properties of the stream channel (channel pattern) to infer sediment transport and depositional processes. The forward physical approach was discussed through the introduction of the energy terms that are known to drive sediment transport and the terms that resist entrainment. Sediment in rivers is transported in two modes: as bedload and as suspended load. Bedload is coarse material and is defined as the material that moves in contact with the bed. No universal bedload transport function exists, however several approaches to sediment transport have been investigated. Suspended sediment is the material that is transported within the water column. Sedimentation of suspended sediment occurs when the fall velocity of the sediment is greater than the turbulent eddies suspending the sediment within the water column. The inverse approach uses channel morphology to provide information on the antecedent condition of the channel. In the final sections, sedimentation related to pipeline construction and the fate of sediment introduced into northern rivers were reviewed. The last section discusses measurable variables for the development of a sedimentation algorithm and provides recommendations for next steps.

MEASURABLE VARIABLES FOR ALGORITHM DEVELOPMENT

As discussed in the previous sections, the problem of understanding the fate of sediment and therefore sedimentation may be investigated in one of two ways: a forward physical approach or an inverse morphological approach. The first involves using known physics to predict sedimentation. The second is an inverse approach that uses the observed properties of the stream channel to infer sediment transport and depositional processes (Church 2006). Used together the forward and inverse approaches should provide a robust method for the estimation of sedimentation on a channel bed downstream of a river crossing.

The inverse approach, using channel morphology, provides information on the antecedent condition of the channel and provides an integration of past conditions of sediment input, discharge, etc. It also provides information on the transport capacity of the channel; supply limited channels have greater transport capacity than transport limited channels. This approach is not strictly predictive however and it is only useful within the reach.

Using the forward approach to predict the susceptibility of a river section to the deposition of sediment on the bed, the background sediment supplied to the channel and the capacity of the channel to transport sediment downstream need to be estimated. The annual amount of background suspended sediment supplied to a channel can be estimated using the sediment yield curve. For bedload sediment, discharge relationships can be derived from measurements at a cross-section over a range of flows by measuring or modeling transport rates to develop a bedload sediment rating curve.

The downstream zone of influence of the sediment input is a function of the volume and grain size of the sediment input and the transport capacity of the downstream channel. Several variables are commonly used to describe the transport capacity of the river system, including shear stress, specific stream power and unit discharge. Controls on deposition include critical shear stress for deposition and sediment grain size.

An approach to predicting the fate of introduced sediment downstream of a crossing would therefore include spatial modeling using GIS. Channel characteristics such as width (w), depth (d), velocity (v), and grain size vary systematically downstream with bankfull discharge (Q_{bf}). Downstream hydraulic geometry equations take the form:

$$w = aQ_{bf}^{\ b}$$

$$d = cQ_{bf}^{\ f}$$

$$v = kQ_{bf}^{\ m}$$

Where: $Qbf = wdv = aQ_{bf}^{\ b} \text{ x } cQ_{bf}^{\ f} \text{ x } kQ_{bf}^{\ m}$, and therefore $\text{a x c x k} = 1$ and $\text{b} + \text{f} + \text{m} = 1$.

The bankfull discharge entered into the equation can be estimated as the flood with a 1.5-year recurrence interval ($Q_{1.5}$) for any point in the river network from regional flood frequency curves. Flood frequency curves use drainage basin area to predict a discharge of a given flood frequency.

Sedimentation may occur during discharges that are higher or lower than bankfull. The frequencies of low and high flows can be estimated to aid the prediction of the temporal aspect of sedimentation. Pipeline construction will likely occur during low flow conditions, while spoil piles will be eroded at higher than bankfull discharges.

Because the deposition of fine sediment is related to the velocity of the flow, the susceptibility to deposition of different grain sizes in downstream locations can be estimated. Slope data can be derived from digital elevation models. Shear stress, specific stream power, and unit discharge at downstream locations can therefore be estimated using the slope and downstream hydraulic geometry equations. Hydraulic geometry equations would need to be developed for the region to provide reliable results.

Total transport capacity is related to the size of the channel for both bedload and suspended load. For bedload, larger rivers have a greater total sediment discharge for a given unit sediment discharge ($kg/m^2/m$) because the unit discharge is multiplied by the channel width. For suspended sediment, larger rivers have a greater discharge and therefore can carry a greater sediment load (sediment load = Q x C_o). River scale therefore is a large factor in the transport capacity of a channel.

NEXT STEPS FOR ALGORITHM DEVELOPMENT

The logical next steps in the development of a sedimentation algorithm for the FRAT will use the forward and inverse approaches. This requires hydrological analysis, GIS analysis, and fieldwork. The next steps include:

1. Developing regional flood frequency curves for peak and low flows from Water Survey of Canada (WSC) data.
2. Documenting the types of channel patterns located within the study area from aerial photographs or remote sensing.
3. Field measurements of the characteristics of channel patterns within the study area.
4. Development of hydraulic geometry equations from the field measurements to predict channel characteristics downstream of crossings.
5. GIS analysis to determine the drainage basin area, slope, discharges of different return intervals, velocities, etc at different locations downstream of the crossings.
6. Development of an algorithm based on analysis results.

SUMMARY

It is possible to predict the fate of sediment input into a channel system both immediately downstream of a site and farther downstream using several different techniques. These include characterizing the river channel pattern and bed sediment characteristics at the site and using GIS analysis of the downstream spatial patterns of grain size, shear stress, stream power, and other variables that predict sediment transport capacity and sediment deposition.

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