Sediment and Sediment-Assisted Nutrient Transfer in Small Agricultural Watersheds in Southwestern Ontario

by

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ABSTRACT

SEDIMENT AND SEDIMENT-ASSISTED NUTRIENT TRANSFER IN SMALL AGRICULTURAL WATERSHEDS IN SOUTHWESTERN ONTARIO

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Sediment and nutrient export was evaluated in a small agriculture-dominated watershed that drains into Rondeau Bay, Lake Erie. Understanding the dynamics between runoff, sediment entrainment, and nutrient transport is key to mitigating the detrimental impacts of agricultural practices on water resources. In this study the following hypothesis was tested: the quantity and quality of suspended sediment yields in agricultural settings controls nutrient transfer from runoff. Stream discharge and water quality was monitored at three locations along a tributary reach within the Rondeau Bay basin during the 2013 growing-harvest season. This research concludes that agricultural-based nutrient loading into Lake Erie is sediment-assisted and that this sediment potentially derives from in-channel and tile drain sources. Nutrients were potentially linked to the stream with tile drains allowing for direct Phosphorus and Nitrogen transfer. The findings have important implications for future soil loss and thus nutrient loading from agricultural settings, especially during extreme events.

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Chapter 1. Introduction

Sediment pollution from agriculture is the most common water quality impairment of fluvial systems, with notable economical and environmental implications (Environmental Protection Agency, 2012). In North America, the cost for mitigating water impairments relating to sediment pollution ranges from $20 billion to $50 billion annually (Osterkamp et al., 2004). However, the majority of streams and rivers are not monitored by federal agencies (Gray & Gartner, 2009). As a result, there is a lack in available streamflow and suspended sediment data, which itself is a critical limiting factor in the sediment pollution mitigation process.

In agricultural watersheds, streams are enriched with above-normal suspended sediment concentrations (SSC) due to increased erosion rates associated with various agricultural land management practices (Verhulst et al., 2010). High SSCs reduce water quality, disrupt watercourse drainage, and deteriorate aquatic habitats, among other detrimental effects (Carpenter et al., 1998). In addition, sediment adsorbs and consequently transports nutrients to nearby stream networks and water bodies (Ballantine et al., 2009; Carpenter et al., 1998). As a result, researchers often incorporate both sediment and nutrient monitoring in an effort to better understand the relationship between the two variables in agricultural settings. Phosphorus (P) and Nitrogen (N) compounds are of particular interest within the literature, in regards to agricultural-based nutrients, given their occurrence in farm fertilizers and connections to algal blooms (e.g., Ballantine et al., 2007; Culley & Bolton, 1983; Fraser et al., 1999; Gaynor & Findlay, 1995; Quinton et al., 2001; Sharpley et al., 1992). These works illustrated a positive relationship between SSC, and P and N loading. More specifically, P and N loading is often associated with clay-sized particle abundance, because clay particles are preferentially transported and have an increased surface area relative to larger grain sediment (Quinton et al., 2001). Local stream variations, and the dynamic nature of sediment sources and mobilization complicates the sediment-nutrient relationship (de Vente et al., 2007). As a result, it is a considerable challenge to predict sediment and nutrient movement in the environment. Nonetheless, researchers can make deductions as to sediment source contributions and sediment transport by studying the sediment response to hydrometeorological inputs. In doing so, it is possible to develop sound management strategies to mitigate sediment and nutrient pollution in agricultural watersheds, and improve water quality.

1.1 The Lake Erie Context

Over the last several decades, multiple studies focused on understanding the key processes governing sediment and nutrient transfer into the Great Lakes. The initial emergence of algal blooms in Lake Erie during the 1960's led to the signing of the Great Lakes Water Quality Agreement (GLWQA), in an effort to mitigate agricultural-derived nonpoint source pollution into the lake (Environmental Protection Agency, 1978). At that time Lake Erie was eutrophic due to nutrient enriched waters causing excessive algal blooms, fish deaths, and a loss in lake related recreational activity (de Pinto et al., 1986). The GLWQA was initially considered successful because nutrient concentrations were lowered to tolerable levels. However, Lake Erie continued to experience algal bloom emergences. Recent water quality analyses indicate that Lake Erie is still eutrophic (Gilbert et al., 2006; Michalak et al., 2013), and summer 2011 satellite imagery confirmed the largest recorded algal bloom to date in the lake (Michalak et al., 2013; Figure 1.1).

Lake Erie water conditions are potentially related to recent changes in agricultural land management practices. For example, no-till operations, tile drainage implementation, and fertilizer application have increased in Southern Ontario (Stats-Canada, 2007; Denault, 2010; Michalak et al., 2013). Collectively, these changes impact surface water composition draining into the Great Lakes. No-till operations result in nutrient buildup on the surface, instead of being mixed into the soil through tillage (Sharpley, 2003). Tile drains act as a sediment and nutrient conduit linking farm fields directly to draining streams (Sharpley, 2003; Sims et al., 1998). Sediment entrainment and nutrient loading is potentially worsened by changes in Southern Ontario climate, which includes increased storm abundance and intensity since 1970 (Adamowski et al., 2003; Stone et al., 2000). Thus, there is renewed concern for sediment and nutrient pollution in the Great Lakes.

This primary objective of this thesis is to evaluate the hydrological, sedimentological, and nutrient response to summer rainfall events in a small agricultural watershed in Southwestern Ontario. Furthermore, in building a dataset to evaluate the connection between hydrometeorology and geomorphic processes, this study contributes to the calibration and validation of environmental models used in small watersheds. The findings serve to provide general insight into sediment and nutrient dynamics in agricultural settings under varying meteorological conditions, and to contribute to our understanding of the ecological degradation of freshwater bodies.

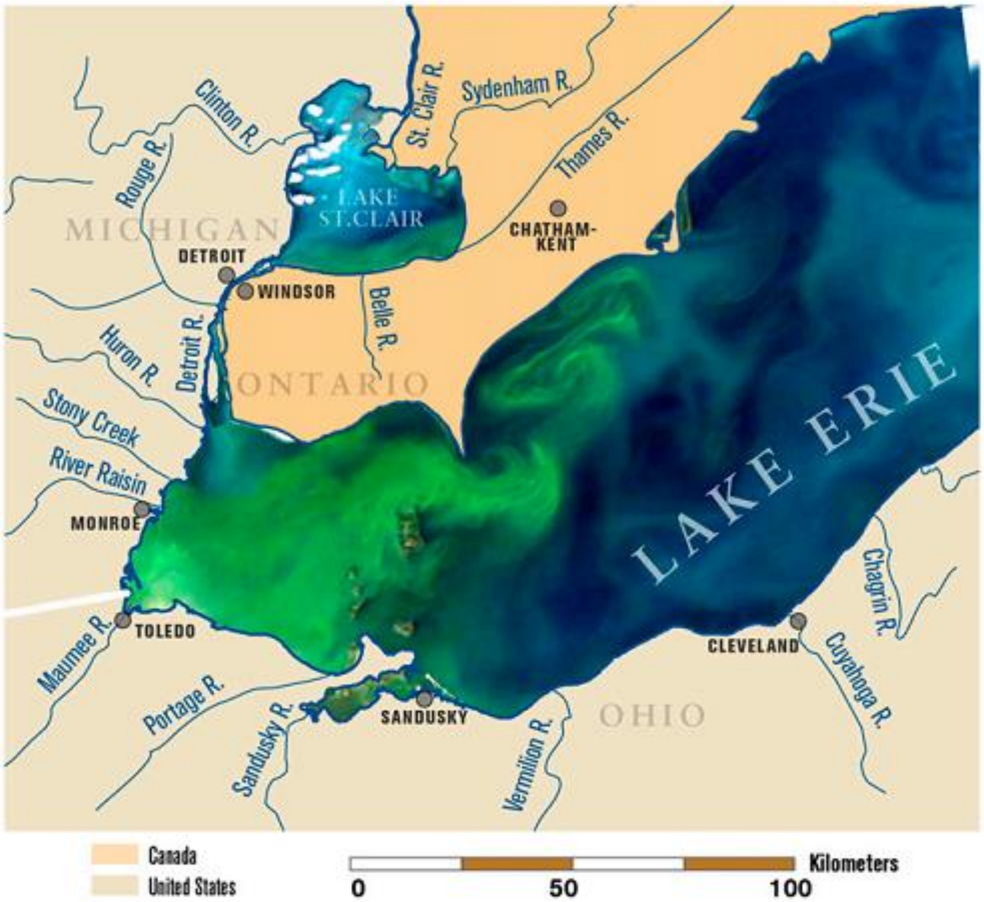


Figure 1.1: September 3, 2011 MODIS satellite imagery of Lake Erie showing the lake-wide algal bloom (algae abundance is depicted by the dark to light green shading on both Lake St. Clair and Lake Erie). The image reveals that the western portion of the Lake Erie was almost fully covered with algae and was expanding towards the basin center (Michalak et al., 2013).

Chapter 2. Literature Review

2.1 Introduction

The following literature review addresses the overarching factors, which contribute to sediment mobilization and transport from agricultural landscapes, as well as the role of sediment in transporting nutrients within water pathways. In summary, sediment mobilization and transport dynamics are discussed with regards to particle entrainment theory, hydrometeorological inputs, event recurrences, the resulting discharge - suspended sediment concentration (SSC) relationship and suspended sediment particle size distribution, and the suspended sediment - nutrient relationship. Additionally, varying sediment sources impact sediment availability for transport. Soil susceptibility to erosion is governed by multiple factors including; soil erodibility, soil moisture, vegetation cover, and agricultural land management practices. There is a focus on the literature from Southern Ontario to establish a background for the research undertaken in this thesis.

2.2 Hydrometeorology

2.2.1 Rainfall Inputs

Rainfall inputs lead to the removal and transport of soil and rock particles through water erosion. Water erosion occurs through rain splash forces as well as the resulting thin surface flow whose erosive potential is increased by turbulence generated by raindrop impact (Ellison, 1945). Water is the most important erosion agent, although wind is a contributing force (Foster, 1991). Rainfall generated surface runoff exports entrained sediment from watersheds by way of flow pathways (e.g., rills, gullies, streams, rivers, tile drainage). In general, runoff fluxes vary accordingly with rainfall event magnitude, duration, and distribution (Quinton et al., 2001). Long duration storms, which produce large rainfall and runoff volumes, result in increased suspended sediment fluxes (Bruce et al., 2006; Rudra et al., 1989). Though, the most severe and thus erosive rainfall often lasts only a short time (Adamowski, et al., 2003; Bruce et al., 2006). In addition, residual soil moisture following rainfall inputs reduces the soil infiltrative capacity and promotes surface runoff.

In many cases, infrequent high-magnitude storm events account for the majority of annual sediment transport from agricultural landscapes (Rudra et al., 1989; Steegen et al., 2000). As a result, many researchers monitor individual rainfall events instead of continuous field monitoring. Rudra et al. (1985, 1989) compiled ~30 years of event-based soil loss data from hillslope plots in Guelph, Ontario. Rudra et al. (1985, 1989) reported that a single high erosion event each year comprised the majority (mean of 60%) of annual soil losses. Steegen et al. (2000) reported that a single rainfall event constituted approximately 68% of the overall denudation, which occurred during a 14-month observation period in a Belgium catchment. Quinton et al. (2001) reported that high magnitude events accounted for approximately 50% of the sediment yield from agricultural fields over a six-year period in the United Kingdom. Quinton et al. (2001) concluded it was thus necessary to identify both low and high magnitude event contributions. High magnitude events also have lasting impacts on local hydrological processes through soil saturation and surface ponding (Caverly et al., 2013; Wainwright, 1996). For example, Caverly et al. (2013) reported that soils remained saturated at least nine days after two consecutive high intensity (~200 mm) tropical storms in a small watershed (21 ha) in the United States.

2.2.2 Rainfall Event Recurrence

Adamowski et al. (2003) evaluated the intensity-duration-frequency curves to quantify events as an occurrence probability factor using data from 1970 to 1998 in Southern Ontario. Adamowski et al. (2003) reported that rare 50, 25, 10, 5 and 2 year return period rainfall events exhibited a 7 - 16% increase in short duration rainfall intensity (e.g., 30 minutes) from 1970 to 1998 in Southern Ontario. Stone et al. (2000) reported that spring and summer heavy rainfall event frequency increased between 4 - 5% per decade from 1960 to 1990 in Southeastern Canada. Kunkel et al. (2000) reported that total annual precipitation in Ontario has risen by 1-3% per decade over the last 30 years, which suggests that as event frequency increased, so did magnitude. Adamowski et al. (2003), Kunkel et al. (2000), and Stone et al. (2000)'s findings have implications for long-term sediment transfer trends. For example, the associated increase in sediment yield ranged up to 20% (Bruce et al., 2006; Table 2.1).

2.2.3 Flow Response to Rainfall Input

Streamflow response varies with spatial and temporal variations in rainfall input, and watershed characteristics, which influence the time taken for water inputs to reach the draining stream. Rainfall distribution influences soil moisture conditions, effectively altering overland and groundwater flow conditions and consequently streamflow response. As a result, rainfall event analyses often involve antecedent soil moisture classification to account for antecedent moisture conditions (Table 2.2). Streamflow response is generally characterized by a measure of the elapsed time between the occurrence of rainfall input and the occurrence of peak runoff (Rao & Delleur, 1974). In small watersheds flow response time depends primarily on hillslope travel duration, as opposed to stream travel time (Inamdar, 2007; Williams, 1989). This is because rainfall inputs to outer watershed hillslopes have increased travel time to the watershed outlet, and may not contribute to peak flow. Flow response time is also affected by in-channel vegetation or woody debris accumulation, which obstruct flow and lead to reduced peak discharges due to flow obstruction (Montgomery & Buffington, 1998). Other factors, including tile drain practices are considered to shorten the pathway between draining streams and adjacent fields, resulting in an accelerated response to rainfall inputs (Robinson, 1989, 1990).

2.3 Sediment Mobilization and Transport Processes

2.3.1 Sediment Entrainment

At the particle scale, erosion is difficult to model given the dynamic and microscopic nature of the system (NiÑo et al., 2003). As a result, traditional approaches to the erosion problem focused on the entrainment threshold for individual particles (e.g., Bernoulli, 1783; Hjulström, 1935; and Shields, 1936). The mathematics governing particle entrainment within fluvial systems is based on the work by Bernoulli, Hjulström, and Shields. Bernoulli's principle (1783) states that a rise in fluid velocity is accompanied by a decrease in fluid pressure. This implies that low-pressure zones are created as fluid flow increases over a given particle bed, lowering grain resistance to uplift into the moving fluid. Hjulström (1935) is renowned for his determination of the Hjulström curve. The curve indicates for a given particle diameter flow velocities that result in sediment deposition, transport, or entrainment. Shields hypothesized that in order for a particle to become entrained in a flow, a critical shear stress boundary dependent on particle size and density must be exceeded (Equation 2.1).

$$\Theta_* = \frac{\tau}{(\varrho_s - \varrho)gD} \qquad \text{Equation 2.1}$$

Where Θ_* is a parameter describing entrainment initiation, τ is shear stress, ϱ_s is the sediment density, ϱ is the fluid density, g is the acceleration due to gravity and D is the particle diameter. Such traditional approaches do not fully capture entrainment dynamics. For instance, Hjulström (1935) and Shields (1936) assume uniform grain shape and are thus only applicable for single particle entrainment. Particle-particle interaction dynamics, which exist within a particle network, are ignored. Shields (1936) fails to account for particle size distribution and cohesion influences (NiÑo et al., 2003). Furthermore, Hjulström (1935) and Shields (1936) defined a relatively wide range of flow conditions in which incipient motion occurred, and is not useful for pinpointing the instance of particle entrainment. In summary, traditional entrainment models are simple to apply but each overlook key process elements, which contribute to sediment flux complexity.

2.3.2 Discharge-Suspended Sediment Concentration Relationship

Sediment yield from a given watershed is estimated from discharge and SSC (Walling, 1977). Traditional sediment rating curves provide continuous sediment loads by assuming a linear or power-law relationship between streamflow and SSC (Walling, 1977). However, the relationship between discharge and SSC is not as straightforward as the sediment-rating curve implies due to hysteresis. For instance, antecedent soil moisture or sediment source conditions generated by a prior event (or lack thereof) impact the discharge-SSC relationship pattern (Klein, 1984; Steegen et al., 2000; Williams, 1989; Walling, 1977; Wood et al., 1977). As such, the largest recorded SSCs do not always coincide with the hydrograph peak for a given event due to variations in sediment source availability and concentration time (Steegen et al., 2000). For example, during a runoff event the most easily transportable sediment is mobilized early, consequently the availability of comparably erodible sediment for transport by the next event is diminished. In this example, material exhaustion by the initial event produces a chronological clockwise relationship with flow. The three main discharge-SSC classes (Table 2.3) are determined as a function of travelling time and distance of source area to the watershed outlet (Williams, 1989). Researchers associate each discharge -SSC class with potential contributing sediment sources (Klein, 1984; Williams, 1989). The premise is that sediment travelling longer distances across a given watershed (e.g., upland sources) has a particular and traceable impact on the discharge-SSC curve shape (Klein, 1984; Williams, 1989). For example, clockwise curve patterns are interpreted as within-channel sediment sources, whereas counter-clockwise patterns infer upland hillslope sources (Table 2.3).

2.3.3 Sediment Particle Size Characteristics

Investigating the character of suspended sediment is important with regards to source identification and nutrient transport. The relationship between sediment particle size and sediment transport and channel evolution is well studied (e.g., Quinton et al., 2001; Xu, 2002). Particle size often reflects the surrounding land surface composition, allowing for source identification, and is discussed below. There is evidence that sediment particle size has a positive correlation with discharge (Steegen et al., 2000; Xu, 2002). This is consistent with traditional particle entrainment theories (e.g., Shields), that increased fluid velocity ultimately allows for increased energy to entrain and transport larger particles. However, this relationship is not always reported due to complexities associated with variable sediment source availability and supply (Walling & Moorehead, 1989). Furthermore, suspended flocculated particles complicate the discharge - sediment particle size relationship if disaggregation occurs prior to analysis

(Slattery & Burt, 1997). Generally, a portion of the total sediment yield is transported as large grain aggregates, only to be gradually broken up by turbulence downstream (Walling & Moorehead, 1989). Consequently, downstream disaggregation results in increased fine particle abundance with increasing discharge and turbulence. The suspended sediment particle size distribution is sensitive to varying flow conditions and sediment sources (Walling & Moorehead, 1989).

2.3.4 The Suspended Sediment-Nutrient Relationship

Nutrients such as Nitrogen (N) and Phosphorus (P) are able to adhere to fine suspended sediment particles creating a transport pathway through watercourses, and as a result N and P content is generally correlated with increasing SSC (Figure 2.1). Hunter and Walton (2008), Poirier et al. (2012), and Quinton et al. (2001) each reported SSC - N or P correlation values greater than $R^2 = 0.84$, and further illustrated that N and P associate with fine-sized sediment (Ballantine et al., 2009; Quinton et al., 2001; Stone & English, 1993; Wall et al., 1996). Clay-sized particles in particular are notable nutrient transport agents due to their relatively large surface area, high exchange capacity and charged surfaces (Figure 2.2; Follett & Delgado, 2002; Sharpley et al., 1990; Stone & English, 1993). This marks an important consideration given our understanding that fine particles are susceptible to erosion and thus preferentially transported (Quinton et al., 2001). In Southern Ontario, the potential for sediment-assisted nutrient loading is high because the majority of suspended sediment transported into the Great Lakes falls within the clay - silt fraction due to the supply from glacio-lacustrine deposits (Stone & Saunderson, 1992). It is important to note that sediment-associated N and P estimates exhibit high variability, indicating that changes occur to compound form and thus bioavailability during transport (Sharpley et al., 1992). This is attributed to the dynamic nature in which sediment is transported and deposited within any given landscape (Sharpley et al., 1992). For example, estimated sediment-associated biologically-available P (P in forms directly available for algal growth) ranged from 2 - 60 % for Lake Ontario (Bannerman et al., 1975). The projected rises in rainfall and sediment yield in Southern Ontario (Table 2.1) has major implications for nutrient loading into the Great Lakes, given the association between suspended sediment and nutrient content.

2.4 Sediment Sources

2.4.1 Critical Source Areas

Agricultural land management practices place pressure on soil structure and its resistance to erosion (Verhulst et al., 2007). As a result, zones, which supply sediment and nutrients, vary accordingly with the existing management parameters in a given watershed. Areas abundant in sediment, which are also subjected to the erosive potential stemming from land management influences, are referred to as critical source areas (CSA) (Ballantine et al., 2009; Pionke et al., 2000). Potential CSA's are often identified through field surveys, remote sensing, or environmental modelling techniques prior to field monitoring (Baigorria & Romero, 2007; Ballantine et al., 2009; Davis & Fox, 2007). Common CSA's are classified as: surface soil erosion; upland mass wasting; floodplain erosion by rivers; streambank erosion; in-stream sediment remobilization; and sediment loading from upstream agricultural land management practices, mining, and forest logging (Davis & Fox, 2008; EPA, 2004).

CSA's may be further categorized as point or nonpoint pollution sources (Carpenter et al., 1998). Point sources are considered as confined, discrete sources, from which nutrients are directly discharged. Examples include wastewater effluent, runoff and infiltration from animal feedlots, or runoff and infiltration from waste disposal sites (Carpenter et al., 1998). Point source pollution discharges tend to be continuous in nature with low variability (Jarvie et al., 2010). Point sources are generally easily monitored and regulated, as mitigation measures may be subjected directly to the contributing source. Alternatively, nonpoint source pollution describes pollution stemming from diffuse sources. Major nonpoint source pollution includes sediment and nutrient losses from agricultural fields as a result of land management practices (Carpenter et al., 1998). Nonpoint source pollution is therefore considered to be flow dependent because it is linked to runoff generating events, which occur intermittently (Jarvie et al., 2010). Consequently, nonpoint source pollution is relatively difficult to control and a likely chief contributor to poor water conditions in freshwater bodies.

Sediment transfer dynamics are influenced accordingly by the contributing CSA. Generally, sediment is quickly delivered from channel-based sources to the outlet due to the close proximity of a flowing transport pathway (Klein, 1984, Williams, 1989). Comparatively, upland sources exist further from the outlet, where sediment is more likely to undergo deposition and remobilization, thereby elongating source contribution time (Ballantine et al., 2007; Klein, 1984). The rapidity in which mobilized sediment travels the watershed extent relates to the rate of nonpoint source pollution, given the SSC-nutrient relationship. Watershed sediment budgets are the quantification of overall sediment flux from monitored CSA's. The approach must account for spatial and temporal variability, as watersheds generally contain multiple sources and sediment fluxes vary in space and time (Walling et al., 2002). As a result, research often entails averaged annual budgets, which fail at isolating event-based flux contributions.

2.4.2 Sediment Source Identification

Researchers employ sediment 'fingerprinting' techniques to estimate the relative sediment supply from differing CSA's. Fingerprinting operates on the principle that spatial and temporal variations in sediment properties reflect the variations in the relative contributions from distinguishable sources (Collins et al., 1998). Common fingerprinting methods are to investigate the discharge-SSC relationships based on the pattern shape (Table 2.3). Discharge - SSC pattern interpretations downfall as a fingerprinting means because there is no physical evidence (e.g., tracers) to support that the sampled sediment originated from a given location. It is therefore possible that sediment has followed unrecognized delivery pathways prior to sampling.

Alternatively, more direct fingerprinting approaches include using physical and chemical particle property signatures, which are unique to specific sources located within the watershed. Identifiers include physical (e.g., grain size distribution, organic matter content) and radiometric properties (Davis & Fox, 2008; Walling, 2005). For instance, fluvial sediment grain size distributions can be attributed to specific CSA's if grain size properties associated with each source are known (Walling, 2005). Once a traceable variable is defined, relative CSA contributions are estimated using a multi-variate mixing model (Equation 2).

$$R_{es} = \sum_{i=1}^{n} \left(\frac{C_{ssi} - (\sum_{s=1}^{m} C_{si} P_s)}{C_{ssi}} \right)^2 \qquad \text{Equation (2.2)}$$

Where, R_{es} is the sum of the squares of the residuals, *n* is the number of tracer properties involved, *i* is the tracer property, C_{ssi} is the tracer property concentration, C_{si} is the tracer property mean concentration, and P_s is the relative proportion from the source group *s* (Walling, 2005). Since its inception, multiple research groups have applied the technology with reported success (e.g., Fox and Papanicolaou, 2007; Walling et al., 2002). However, much remains unknown as to which tracers are better suited for various environments (Davis & Fox, 2008). Tracer effectiveness largely depends on how it will interact with the surrounding environment and change throughout the course of transport (Davis & Fox, 2008). For example: physical tracers are susceptible to weathering forces (e.g., particle erosion into finer fractions).

2.5 Factors Affecting Mobilization Rates

2.5.1 Soil Erodibility

Soil structure, texture, organic matter content, and permeability each influence susceptibility to erosion (Verhulst et al., 2007). Such physical components are products of the underlying parent material and developed from varying degrees of physical and chemical weathering. In Southern Ontario, much of the surficial geology is glacial till, which is composed of unsorted, disaggregated sediment. The material heterogeneity allows the soil to compact, resulting in poor drainage and increased surface runoff (Hendry, 1982). Soil susceptibility is characterized by the soil erodibility factor (K). Wischmeier & Smith (1978) define K as a dimensionless value ranging from 0 (low susceptibility) to greater than 0.05 (high susceptibility), and is based on measurements attained from extensive plot simulations. In Ontario, derived K values range from 0.003 for loamy sands, to 0.049 for clay loams, to 0.069 for silt loams (Wall et al., 1988; Wischemeier & Smith, 1978). The small grain size associated with clays and silts leads to their preferential transportation as exemplified by their relatively high K (Quinton et al., 2001). As a result, regions abundant in fine material are likely to produce runoff characterized by high SSCs (Quinton et al., 2001).

Soil erodibility is further controlled by seasonal soil moisture changes (Chow et al., 2000; Wall & Cereal, 2002). Saturated soils are characterized by reduced infiltration rates and increased sediment vulnerability to surface runoff. Studies conducted on multiple Ontario soils report that soils were most prone to transport during spring and early summer months due to increased soil wetness. The soils were less susceptible and thus less likely to become entrained during late summer and fall months (e.g., September - October), as dry soils absorb more water prior to saturation and reduce runoff generation (Kirby & Mehuys, 1987; van Vliet & Wall, 1981; Wall et al., 1988).

2.5.2 Vegetation Presence

Vegetation presence prevents erosion through raindrop interception, wind obstruction, or soil strengthening via root fixing and soil moisture uptake (Verhulst et al., 2007; Zuazo & Pleguezuelo, 2009). The relationship between vegetation cover extent and erosion rates is reported as a negative exponential curve (Figure 2.3; Rogers & Schumm, 1991; Zuazo & Pleguezuelo, 2009). Farmers typically plant in spring and harvest the crops in late-summer to fall (September-October). As such, summer crops are fully matured allowing for greater protection from erosive agents and increased root water uptake, as compared to the early-spring budding and late-fall post harvest periods (Steegen et al., 2000; Zuazo & Pleguezuelo, 2009). In various cases, particularly fields undergoing no-till management, the avoidance of overturning the soil results in the formation of a surface crust (e.g., Steegen et al., 2000; de Vita et al., 2007). Under such circumstances the crust may act as a seal, increasing the potential for nutrient transport through increased surface runoff (Steegen et al., 2000).

Crop type is important for understanding agricultural erosion as varying crops result in varying cover extents (%) and soil moisture uptake. Two dominant Southern Ontario crops include soybean and corn (Stats-Canada, 2007). Studies suggest increased soil and runoff losses from soybean plots as compared to corn (e.g., Ghidey & Alberts, 1998; Laflan & Moldenhauer, 1979). Though, Ghidey and Alberts (1998) reported such runoff / soil loss differences at less than 12 % for small fields in Montana, US. In general, studies reported increased surface residue cover from corn, leading to increased infiltration and less runoff (Ghidey & Alberts, 1998; Laflan & Moldenhauer, 1979).

2.5.3 Agricultural Land Management

Conventional and Conservation Tillage

Although sediment erosion occurs naturally, agricultural land management practices impact the erosion process (Verhulst et al., 2007). Land management accelerates physical processes, which promote agricultural productivity. For instance, conventional-tillage (CT) and ploughing operations aerate upper soil layers, facilitating crop planting, and mixing crop residues and organic material evenly throughout the soil. However, the mechanical soil overturning process associated with CT compromises soil structure integrity by destroying soil aggregates, rendering the soil more susceptible to erosional agents (Triplett & Dick, 2008; Verhulst et al., 2007). Studies show that aggregate and aggregate binding agents (e.g., organic matter, macrofauna) are more abundant in uncultivated soils as compared to cultivated CT soils (Beare et al., 1996 ; Six et al., 1998; Triplett & Dick, 2008), because aggregate formation is interrupted each time the soil is tilled (Verhulst, 2007). In addition, CT topsoils are more susceptible to aggregate breakdown due to reduced organic matter content (Blevins et al., 1998). As a result, tilled or ploughed lands are characterized by increased soil loss rates (Triplett & Dick, 2008).

In comparison, conservation tillage (e.g., no-tillage [NT]) designates a system in which tillage is reduced or avoided completely (Triplett & Dick, 2008). Fields undergoing conservation tillage allow for crop residue accumulation on the soil surface, acting as a cover against erosive agents (Verhulst et al., 2007). Conservatively tilled fields are often linked to reduced sediment losses caused by effective water infiltration (Lal, 1976; Roth & Capel, 2012; Triplett & Dick, 2008). A 42-year erosion study in Ohio comparing NT effects to CT demonstrated the erosion control effectiveness for each: NT plots showed an average elevation difference of 9.0 cm compared to CT plots for uniform slopes over this time (Triplett & Dick, 2008). Lal (1984) reported 0.002 t ha^{-1} loss compared to 3.8 t ha^{-1} for respective NT and CT plots during a peak 42mm rainfall event in Western Nigeria. Roth and Capel (2012) demonstrated negligible losses (0.11 kg m^{-1}) from simulated NT plots, as compared to conventional methods (3.4 kg m^{-1}) in a USGS water quality assurance report.

The tillage impact on nutrient transfer is more complicated. Gaynor and Findlay (1995) reported up to twice the P and Orthophosphate (PO_4^{3-}) transfer from conservatively tilled fields in Southwestern Ontario, relative to fields undergoing CT. By avoiding tillage, nutrients are not mixed into the soil, which increases the potential for losses to overland flow (Sharpley, 2003). In contrast, outside of Ontario, work by Sharpley et al. (1992) and Ulén et al. (2010) reported diminished P transfer from NT fields. The shift towards more sustainable practices in Ontario (e.g., shifting to NT from CT) marks an important consideration for soil and nutrient transfer. In 1991, 8 % of crop farms reported NT operations. Since then, the number of NT farms has risen to over 30 % (Stats-Canada, 2007).

Irrigation

Across the US, irrigated fields show a two-fold increase in productivity value over naturally rain-fed fields (Sojka & Lentz, 1997). Despite this convenience, irrigation practices contribute to potential soil loss (Skaggs et al., 1994; Trimble, 1997). Irrigation lowers the soil infiltrative capacity through soil saturation. The increase in antecedent soil moisture promotes surface runoff during storm events, thereby contributing to the lateral transport of suspended sediment and nutrients (Skaggs et al., 1994; Trimble, 1997). As a result, fields which are irrigated are often also tile drained to prevent water table rises (Skaggs et al., 1994). In Ontario, approximately 19 % of farms were irrigated in 2006 (Stats-Canada, 2007), which suggests that irrigation is a major factor affecting water quality in the Great Lakes region.

Tile Drainage

Fields are commonly underlain with tile conduits to drain excess water, which also provides a transport pathway for suspended sediment and nutrients (Walling et al., 2002). Often, runoff exported through tile drains constitutes the majority of total runoff delivery from the watershed, as well as a bulk of the total sediment and nutrient output (Culley & Bolton, 1983; Walling et al., 2002). Such is the case for Southwestern Ontario watersheds where approximately 40% of agricultural land is tile-drained (Denault et al., 2010). Culley and Bolton (1983) reported that tile drainage accounted for approximately 60% of the annual surface runoff, 50% of the total suspended sediment flux, and 35% of the total N and P transport. Gaynor and Findlay (1995) reported tile-drain associated suspended sediment and PO_4^{3-} contributions at up to 65% and 68%, respectively. Similar trends were observed elsewhere: In a Southern Quebec watershed, tile-drainage accounted for an estimated 31% of the annual suspended sediment output (Poirier et al., 2012). Walling et al. (2002) report tile-drained suspended sediment output up to 45 % for field plots in the UK.

Nutrient and Pesticide Application

Nitrogen (N) and Phosphorus (P) are essential elements for plant growth and survival (Follett & Delgado, 2002). However, both N and P are generally found to be in short supply within the natural environment. Farmers address the deficiency by supplying their crops with N and P - based fertilizers, thereby enhancing crop growth and overall farm productivity (Carpenter et al., 1998). In addition, pesticide applications are also rich in N and P (Carpenter et al., 1998). Unnaturally high N and P soil content, linked to fertilizer and pesticide applications, is potentially detrimental to ecosystem wellbeing. On average, crops uptake half the total N and P administered (Cassman et al., 2002). The residual nutrient loads are mobilized and exported from the watershed following rainfall events. High aquatic nutrient availability leads to eutrophication, and further negative impacts on water quality (Carpenter et al., 1998). P inputs in particular are considered a primary eutrophying agent (Schindler, 2006). Eutrophication is an environmental concern because it results in decreased oxygen levels, fish deaths, clogged pipelines, and reduced recreational opportunities among other detrimental effects (Carpenter et al., 1998).

P is exported from watersheds as a particulate or dissolved form, with multiple possible sub-compound formations (EPA, 1983). Surface runoff characterized by high SSCs is a major hydrological P pathway, as P readily adheres to particle surfaces (Ballantine et al., 2009). Relatively decreased P fluxes are reported to occur within the dissolved load (Carpenter et al., 1998). Primary N transport mechanisms are atmospheric emission and subsurface leaching, while total N losses in runoff are generally less than 5% (Carpenter et al., 1998). In a given agricultural setting, approximately 50% of applied N is used by crops, 20% evaporates and is lost to the atmosphere as NO_x , N_2O, NH_3, 25% is leached as NO_3, and 5% is lost to runoff as NO_3 (Follett & Delgado, 2002). Agricultural landscapes are therefore major contributors to nutrient loading of adjacent water bodies.

2.6 Conclusions

In summary, major quantities of sediment and nutrients are contributed from agricultural watersheds to surface water systems and freshwater bodies. In response, researchers aim to identify contributing sediment sources and understand sediment transport dynamics in order to lower transfer rates. The rate of sediment and nutrient transfer is largely affected by land management practices (e.g., tillage operations, artificial fertilizers, tile drains). However the transfer process is complicated by variable sediment source availability and supply, and site specific variations. As a result, sediment and nutrient transfer varies in space and time between locations.

In Southern Ontario, agricultural-based pollution of the Great Lakes is evidenced by symptoms of eutrophication, despite long-term efforts to prevent it. The recent provincial-scale movement towards no-till and tile drainage practices are certain to have an impact on sediment and nutrient transfer. However, the impact of these practices on transfer rates is not well understood and tends to vary between studies (Robinson, 1989; Sharpley 2003; Sims et al., 1998). In addition, studies indicate increasing trends in rainfall event frequency and intensity in Southern Ontario, which is expected to impact the sediment and nutrient flux from agricultural watersheds (Bruce et al., 2006). Thus, there is a demonstrated need to expand our understanding of the geomorphic controls in the Great Lakes region.

Tables and Figures

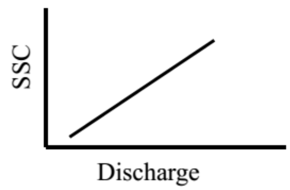
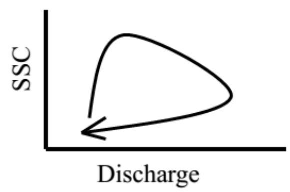
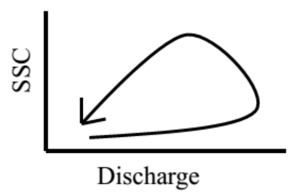
Table 2.1: Seasonal increase in precipitation from 1970 - 2000, and associated model-predicted sediment yield (adapted from Bruce et al. 2006).

Change in precipitation	Change in sediment yield
Increase in frequency of runoff events	Associated % increase in sediment yield
Spring: 4% per decade Summer: 5% - 7% per decade	Spring: 13% - 19% Summer: 14% - 20%

Table 2.2: Antecedent soil moisture classes (AMC) based on past rainfall conditions and crop senescence, as proposed by the US Department of Agriculture (NEH, 1972).

	Total 5 day antecedent rainfall (mm)	
AMC Group	Growing season	Dormant season
I	<13	<36
II	13-28	36-53
III	>28	>53

Table 2.3: Suspended sediment concentration versus flow rate classifications, and potential cause associated with each class.

Class	Discharge-SSC relationship	Discharge-SSC pattern shape	Potential cause	Example reporting studies
1)	Single valued line		Uninterrupted sediment supply from source (s)	Williams (1989)
2)	Clockwise loop		Source exhaustion, bed paving	Salant et al. (2007); Steegen et al. (2000)
3)	Counter-clockwise loop		Highly erodible source soil undergoing long-lasting erosion, seasonal variability	Walling & Gregory (1970); Klein (1984); Williams (1989)

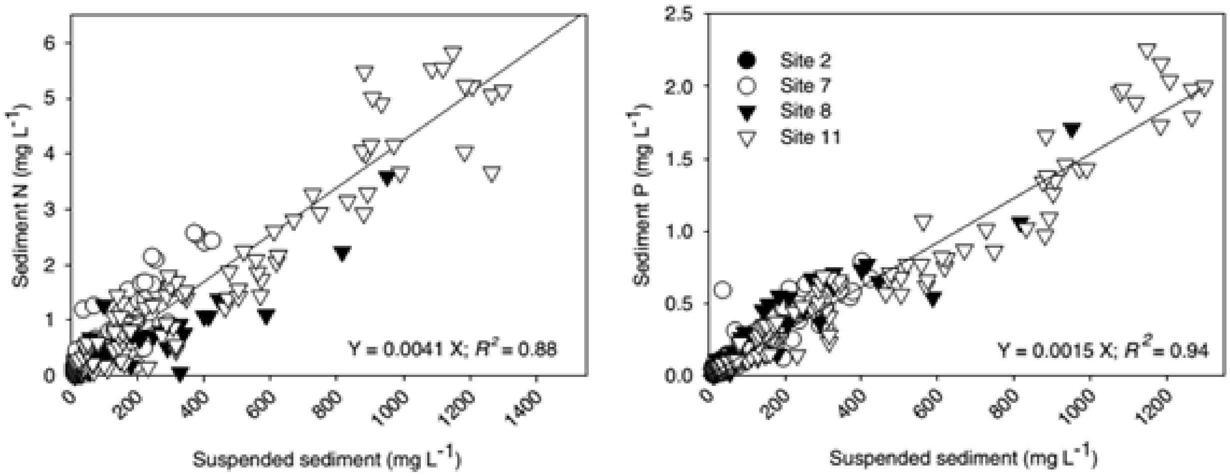


Figure 2.1: N and P concentration positively correlated to SSC as shown for agricultural watersheds in Australia (Hunter and Walton, 2008).

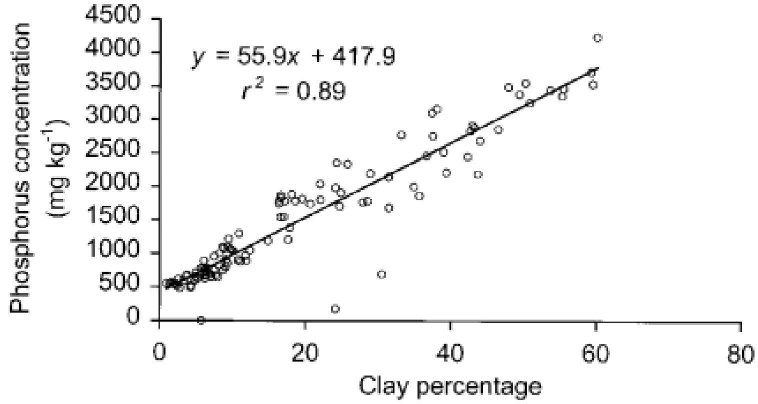


Figure 2.2: Relationship between Phosphorus concentration and clay abundance for UK field plots. A positive trend is observed (Quinton et al 2001).

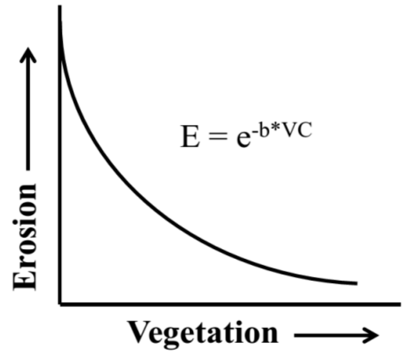


Figure 2.3: Proposed relationship between erosion and vegetative cover, expressed mathematically by Zuazo and Pleguezuelo (2009), where E is the erosion rate, b is a constant based on crop type, and VC is the vegetative crop cover (%) (adapted from Rogers and Schumm, 1991).

Chapter 3. Sediment and sediment-assisted nutrient transfer from a small tile drained watershed under no-till conditions in the Great Lakes region

3.1 Abstract

Sediment and nutrient export was evaluated in a small agriculture-dominated watershed that drains into Rondeau Bay, Lake Erie. The following hypothesis was tested: the quantity and quality of suspended sediment yields in agricultural settings controls nutrient transfer from surface runoff. Stream discharge and water quality was monitored at three locations along a tributary reach within the Rondeau Bay basin during the 2013 growing-harvest season (May to October). Discrete water samples were analyzed in the laboratory for suspended sediment concentration, particle size, and sediment-assisted Nitrogen and Phosphorus content. A mid-season change in contributing sediment sources was inferred based on the observations of suspended sediment transfer and particle size following a high magnitude rainfall event. On July 19th, ~92 mm of rain fell in under 24 hours over the region. This caused ponding in adjacent fields for several days and in-channel debris dams. This extreme runoff event marked an important change in the discharge-suspended sediment response seen in the catchment. This included: 1) a July to September abrupt decrease in suspended sediment concentration; 2) a coincident increase in fine-particle abundance; and 3) evidence of event-scale sediment hysteresis. Estimated total sediment yield over the 6 month monitoring period was ~50 t (0.13 t ha^{-1}) based on the positive relationship between suspended sediment and discharge (R^2 = 0.73, n = 87). The July event contributed approximately 38% of the total sediment yield. Clockwise event hysteresis suggested adjacent and/or likely channel derived sediment sources. Finally, there was a positive relationship between suspended sediment concentration and Phosphorus (R^2 = 0.86, n = 63), Orthophosphate (R^2 = 0.75, n = 63), and total Nitrogen (R^2 = 0.06, n = 63).

Estimated nutrient concentrations all exceeded provincial load guidelines, which suggests that present land management efforts to minimize nutrient loading via surface runoff requires further evaluation. This research concludes that agricultural-based nutrient loading into Lake Erie is sediment-assisted and that this sediment potentially derives from channel sources. Nutrients were potentially linked to the stream allowing for direct Phosphorus and Nitrogen transfer. The findings have important implications for future soil loss and thus nutrient loading from agricultural settings, especially during extreme events.

3.2 Introduction

Agricultural watersheds are characterized by above-average suspended sediment concentrations (SSC) and nutrients. This is due to increased erosion rates associated with various agricultural land management practices (Carpenter et al., 1998; Verhulst et al., 2010). Suspended sediment transfer from agricultural landscapes degrades downstream water quality because as a physical presence, high SSCs reduces water transparency, disrupts watercourse drainage, and covers aquatic habitats (Carpenter et al., 1998). In addition, fine sediments adsorb and thus transports nutrient pollutants within surface runoff to nearby stream networks and water bodies (Ballantine et al., 2009; Carpenter et al., 1998). Pollution caused by agricultural-based sediment and nutrient transfer is the most common cause of water impairment in the Great Lakes region, affecting industries totaling over $40 billion (Environmental Protection Agency [EPA], 2012; Stone & English, 1993).

Water quality in Lake Erie was identified as a serious issue due to agricultural activities in the 1970's (EPA, 1978). In response, nutrient loading reduction strategies were adopted throughout Canada and the United States to reduce eutrophication (EPA, 1978). Nonetheless, Lake Erie has experienced episodic algal bloom re-emergences since the 1970's, and as recently as summer 2011, the largest bloom to date occurred (Michalak et al., 2013). It is possible that Lake Erie's current eutrophic state is due to increased nutrient loading stemming from recent changes in land use. For instance, Ontario reports increases in no-till operations, tile drainage operations, and fertilizer use over the last decade (Stats-Canada, 2007; Denault, 2010; Michalak et al., 2013). Research suggests that no-till prevents fertilizer-based nutrients from being mixed into soils, allowing for rapid nutrient transport in surface runoff, with tile drains linking the nutrient-laden runoff directly to draining streams (Sharpley, 2003; Simard et al., 2000). Other factors, such as increases in rainfall intensity and occurrence throughout Southern Ontario, also promote nutrient loss by increasing local erosion (Adamowski et al., 2003; Bruce et al., 2006; Michalak et al., 2013). Therefore, extreme rainfall events that often lead to increased sediment yield from agricultural watersheds (e.g., Bruce et al., 2006; Rudra et al., 1989; Steegen et al., 2000) have important implications for water pollution in the Great Lakes.

In light of the trends in poor water quality, land use changes, and rainfall increases in Southern Ontario, it is necessary to evaluate agricultural sediment transfer and identify contributing sources in order to mitigate the detriments associated with sediment and nutrient pollution. Insight can be gained by investigating variations in the stream discharge - SSC relationship. For example, chronological clockwise hysteresis patterns occur when transported sediment derives from near or in-channel sources (Klein, 1984; Steegen et al., 2000; Williams, 1989). Furthermore, nutrient transport pathways can be inferred through the relationship between suspended sediment flux and nutrient loading. Current research suggests a connection between surface water nutrient loading and fine soil fractions (Ballantine et al., 2007; Quinton et al., 2001). More specifically, clay-sized particles are often positively correlated with nutrient loading due to their large surface area, high exchange capacity, and charged surfaces (Sharpley et al., 1990). This is important because clay-sized particles are preferentially eroded from source areas and potentially mobilized through frequent, low magnitude runoff events (Fraser et al., 1999; Quinton et al., 2001).

This study proposes that the quantity and quality of suspended sediment yields in agricultural settings controls nutrient transfer from surface runoff, and that agricultural practices such as no-till and tile drains have an impact on the hydrological, sedimentological and nutrient loading response to rainfall inputs. Two primary objectives were considered in order to test this hypothesis: 1) identify sediment mobilization mechanisms and transport processes as they relate to rainfall events, and 2) establish a relationship between transported sediment character (e.g., concentration and grain size) and nutrient loading.

3.3 Methods

3.3.1 Study Site

Water quantity and quality was monitored in a small portion of a tributary draining into Rondeau Bay, Lake Erie, during the 2013 summer (May - October). The monitored reach is ~2.5 km in length, and drains a sub-watershed approximately 3.8 km^2 in area (Figure 3.1). Within the study area, the stream channel ranges from 1 - 2 m in width and 5 - 25 cm in depth during low-flow conditions, though some deeper pools over 50 cm deep exist. The channel is deeply incised with little presence of a floodplain. Bank incisions extend up to 2 m in height. The streambed generally consists of 5 - 25 cm of fine material. The tributary extends southward toward Lake Erie from the elevated Blenheim moraine (Gilbert et al., 2007). Streamflow is generated by the

803 mm of rainfall and the 83 mm of snowfall that is received annually in the area (Environment Canada, 2012). The soils underlying the tributary are classified as a silty clay loam, derived from glacial-lacustrine deposits (Gilbert et al., 2007). The soil is characterized as poorly drained due to the surficial geology (Gaynor & Findlay, 1995). The region is dominated by agricultural activities (e.g., related to crop growth and pastures), and has been degraded by intensive land management practices dating back to the 1960's (Gilbert et al., 2007; Ministry of the Environment, 1982). Farmers have adopted no-till operations over the last several decades, in response to the land degradation (Gilbert et al., 2007). Farming practices are uniform across the watershed. Fields adjacent to the monitored tributary were cropped with soybean, corn, and hay during this study. Seeding occurred early May and crops were harvested throughout October. Tile drainage implementations are in place linking field runoff directly to the stream channel. A dense riparian buffer along parts of the stream was present, this promoted woody debris buildup and dense aquatic vegetation growths. As a result, portions of the stream were waterlogged and stagnant depending on rainfall events throughout the monitoring period.

Recent ecological assessments report high nutrient loadings into the bay, as evidenced by algal blooms and aquatic vegetation growth (Gilbert et al., 2007). Total SSC, Phosphorus, Nitrogen, dissolved oxygen, and E. Coli exceeded proposed provincial levels for the majority of tributaries draining into the bay (Gilbert et al., 2007). Despite poor water quality conditions at present, continuous tributary monitoring for discharge, SSC, and nutrient content is not in place (Gilbert et al., 2007). Furthermore, special concerns have been raised in regards to a number of Species At Risk (SAR), which seek refuge within the Bay. Numerous retention ponds, buffer strips, and treatment wetlands were established in the area (e.g., 2007 - 2010) in response to growing environmental concerns and provincial funding projects, though none were located in the studied sub-watershed.

3.3.2 Data Collection

Precipitation was the primary weather factor that controlled runoff generation in this field site. Precipitation and temperature were recorded with a Davis Instruments, Vantage Pro2 Plus weather station and tipping bucket located nearby (~10 km) in the Cedar Springs Township. Each bucket tip is equivalent to 0.3 mm moisture accumulations. Temperature was monitored at 15-minute intervals. Weather Innovations Consulting Incorporated maintains the weather station.

Three roads intersect the monitored reach: Talbot, Eds, and Front, from which the stream was accessed for gauging and sample collection (Figure 3.1b). Continuous water depth was measured with ONSET Hobo water level loggers installed at each gauging point (Talbot, Eds, and Front) within stilling wells to reduce the impact of water currents on instrument pressure outputs. An additional pressure transducer was located at Talbot station to measure atmospheric pressure. Stream stage was determined by removing the pressure exerted by the atmosphere on the sensor from the total pressure (water and atmospheric pressure) exerted on the submersed sensor, and converting recorded pressures to a water depth measurement. The transducers are accurate to ±0.03% under normal temperature conditions (0 to 40˚C ; ONSET data loggers, 2009). The volumetric streamflow rate ($m^3\,s^{-1}$) was estimated using a stage-discharge rating curve established for each station (Figure 3.2). Discharge was determined by measuring the stream cross-sectional area and mean velocity. Stream velocity was measured with a mechanical current meter (accuracy is ± 1% of measured value).

Gauging at each station, water sample collection, and general maintenance of the site was completed near weekly between May and October 2013. Water samples were kept cool and analyzed for suspended sediment and particle size, as well as total Phosphorus (P), Orthophosphate (PO_4^{3-}; a P form readily available for plant uptake), and total Nitrogen (N). SSC was determined by filtering the sample through a pre-weighed polycarbonate 0.4 um filter. Filter-recovered sediment was rinsed into a SEQUOIA portable LISST (Laser In Situ Scattering and Transmissometry) for particle size determination. Fluvial sediment traps were constructed and anchored in-situ to the streambed upstream and downstream (Front and Talbot station, respectively) to collect sediment in transport. Traps were constructed according to Phillips et al. (2000) submersible trap design. Trap-recovered sediment was collected at several instances throughout the sampling period to characterize pre-cultivation, cultivation, and post harvest-associated suspended sediment. Nutrient spectrophotometry assessments were conducted on collected water samples with a HACH DR/2010 spectrophotometer, following the chemical analysis procedures as approved by the EPA (1998) for wastewater treatment. Persulfate Acid Digestion, procedure #8190, was followed to determine total Phosphorus concentration, as adapted from the Standard Methods for the Examination of Water and Wastewater (Clesceri, 1998). Ascorbic Acid Digestion procedure #8048, was followed to determine Orthophosphate concentration. Persulfate Digestion, procedure #10071, was followed to determine total Nitrogen concentration. Nutrient analysis generally occurred within 24 hours of water sample extraction.

Finally, potential sediment transport pathways and critical source areas were identified through field reconnaissance, involving physical field surveys and OMAF-MRA information contributions (e.g., OMAF-MRA, LiDAR high resolution imagery for Rondeau Watershed). Example transport pathways include: streams, gullies, tile drains, and road culverts. Critical source area identification was based on one or more of the following criteria: existing land uses (e.g., arable, pasture); agricultural land management practices (e.g., tile drained fields, tilled fields), in-stream sources (e.g., eroded channel banks), surficial material, and landscape slope.

3.4 Results

3.4.1 Hydrometeorology

Runoff was derived from rainfall inputs within the studied watershed. During the 2013 field campaign there were 12 distinct rainfall events (e.g., >10 mm day^{-1}) that generated runoff at all three stations (Figure 3.3). Most rainfall occurred between May and July, as single-day (e.g., <24 hour) events. July rainfall exceeded the 30-year monthly average by 100 mm (Environment Canada, 2010). The largest recorded storm occurred July 19th, when ~92 mm was recorded at Cedar Springs over a 24-hour period. In terms of rainfall intensity, the July 19th event recurrence interval amounted to a 1 in 25 year event (Gov. Ontario, 2013). For each rainfall event, stream response time was calculated (Equation 3.1):

$$T_L = T_{PK} - T_{WC} \qquad \text{Equation 3.1}$$

Where, T_L is lag-to-peak or response time to a rainfall input, T_{PK} is the time of peak total discharge, and T_{WC} is the weighted average time of occurrence in the input hyetograph (Rao & Delleur, 1974). Lag-to-peak (T_L) durations measured at Talbot and Eds station were similar due to station proximity, and ranged from 3-7 hours, until October 6th when the measured T_L duration was 9 and 8 hours, respectively. Front station T_L duration ranged from approximately 4-11 hours, though late summer events (July-October) were characterized by the longest T_L durations (7-11 hours). Overall, Front station T_L durations were longer and more variable throughout the monitoring period.

The flow response specific to Talbot, Eds, and Front station (e.g., unaffected by flow accumulation) was estimated by removing flow contributions from upstream stations. For example, rainfall generated flow corresponding to the reach segment between Talbot and Eds station was determined by subtracting the observed discharge at Eds from the discharge at Talbot. During rainfall events, the greatest quantity of flow per unit area was generated between Talbot and Eds station (Table 3.1). Additionally, the Talbot - Eds reach segment was generally characterized by the shortest lag-to-peak. In contrast, the lag-to-peak was relatively slow upstream from Front station, and in between Eds and Front station (Figure 3.4).

3.4.2 Suspended Sediment, Particle Size, and Nutrient Loading

Sediment transfer through the channel was variable throughout the 6-month monitoring period. Increased SSCs were observed at each station, corresponding to increases in discharge. This was evidenced by the positive relationship between discharge and SSC ($R^2 = 0.73$; Table 3.2). The estimated sediment yield from the reach during the monitoring period was ~50 t, corresponding to an overall denudation rate of 0.13 t ha^{-1}. The denudation rate was affected by sediment contributions from the July 19th event, which supplied an estimated ~15 t (or 38%) to the total sediment yield. During the July 19th event, runoff exceeded bank capacity and flooded most of the in-stream sensors. There was notable redistribution of sediments throughout the stream as some sensors were also buried in approximately 10 cm of sediment. There was evidence of ponding in the adjacent fields, which lasted several days following the event. Other factors, including visible changes to bank and channel morphology, and the uprooting of riparian buffer vegetation, support that the July 19th event was a high erosion event.

A variation in SSC and particle size, independent of discharge, was observed after the July 19th event. SSCs were consistently lower after the event at all stations, until September 12 (Figure 3.5). In addition, mean grain size and fine particle abundance underwent an abrupt shift that coincided with the reduction in SSC. The transported material was predominantly finer than 21 µm after the event, accompanied by a reduction in mean grain size, until September 12 (Figure 3.6). Suspended sediment collected within the in-stream sediment traps exhibited a post-July 19th increase in fine particle abundance, in addition to collected water samples. For example, fine particle (< 21 um) composition in the Talbot station traps increased from 45% to 68% between May 31 and July 31, and dropped to 42% on September 25 (Table 3.3). When sampling frequency was sufficient, a non-linear relationship between discharge and SSC was observed during a runoff event. For example, a clockwise hysteresis pattern was apparent for both early (e.g., May 28) and late summer (e.g., October 6) runoff events. There was no clear evidence that indicated grain size varied within a single event.

Trends in Phosphorus loading closely followed SSC. Phosphorus and Orthophosphate content exhibited a significant positive correlation with SSC ($R^2 = 0.85$ and 0.75, respectively, $p < 0.001$; Table 3.2). Water sample Phosphorus and Orthophosphate content ranged from 0.01 to 2.2 mg L^{-1}. A weak relationship was found between SSC and Nitrogen ($R^2 = 0.06$). Nitrogen content ranged from 0.1 to 25 mg L^{-1}. The highest Phosphorus, Orthophosphate, and Nitrogen levels were observed during storm events, corresponding to increases in SSC. Because there was a strong positive correlation between SSC and Phosphorus forms an estimate was made for total exported P. Estimated Phosphorus yield was 0.44 t over the monitoring period, or 1.1 kg ha^{-1}. The estimated Orthophosphate yield was 0.30 t over the monitoring period, or 0.78 kg ha^{-1}. An estimate in total Nitrogen exports through the season was not attempted. There were no clear trends supporting event-scale nutrient loading hysteresis.

3.5 Discussion

3.5.1 Rainfall Inputs and Runoff Generation

Runoff was derived from rainfall inputs, leading to flow generation at the monitored stations. Over ~10 mm of rainfall per day was needed to generate a response in the station hydrograph. For example, 5-10 mm inputs on May 22, June 6, and October 19 did not result in a hydrograph peak (Figure 3.3), which suggests that the water input was stored. During events with rainfall inputs greater than 10 mm day^{-1}, there were differences in flow generation and flow response between Talbot, Eds, and Front station (Table 3.1). The differences were related to differences in tile drain density. Other variables were not considered to have a varying impact on the flow between stations because they were uniform throughout the watershed. For example, fields in the watershed are all under no-till conditions, vary in crop type (e.g., mix of corn, hay, and soy), overlie a silty clay loam of glacial-lacustrine origin, and are gently sloped.

The reach between Talbot - Eds station was characterized by the greatest quantity of flow per unit area, the most sustained flow, and the shortest lag-to-peak following rainfall inputs (Figure 3.4, Table 3.1). There were 10 tile drains per square-km within the Talbot - Eds reach segment. In comparison, there were 1.4 drains per km^2 upstream from Front station, and 5 drains per km^2 between Eds and Front (Figure 3.1). As a result, less event flow was generated from rainfall inputs, flow was sustained for a shorter period of time, and flow lag-to-peak duration was longer at Eds and Front station compared to Talbot station (Figure 3.4). The difference in flow and hydrograph shapes between stations suggests that the density of tile drains was a controlling factor. Other researchers in small watersheds have identified tile drains as major contributors to overall streamflow and streamflow response times, which supports the proposed tile drain impact at Rondeau Bay. Robinson (1989, 1990) reported that tile drainage resulted in an increase in the peakedness of event flows, with shorter response times for multiple small watersheds (< 3 km^2) in the UK. Robinson (1989) suggested that tile drains shortened flow pathways between the studied fields and streams, hence shortening streamflow lag-to-peak times. The flow response data collected at Rondeau Bay study contrasts with that of Cey et al. (1998). Cey et al (1998) monitored and partitioned flow contributions from various sources within a small agricultural stream in Southern Ontario. Cey et al. (1998) found that tile drain contributions from rainfall inputs were delayed and only constituted marginal portions of the total generated flow. At Rondeau Bay, field observations support a delayed tile drains response, in addition to fast a response. For example, photos taken August 22 following two weeks of no rainfall show multiple tile drains flowing freely (Figure 3.8). Flow generation from tile drains is complex and is influenced by a number of site-specific parameters, such as water table height and vegetation stage (Robinson, 1990; Wiskow & Smith, 2003). For instance, crops and riparian vegetation uptake more water from the soil during early growth stages reducing flow potential from tile drains (Evans et al., 1991). There is room for understanding at Rondeau Bay, where tile drains are abundant and potentially contribute large quantities of flow. The dominant role of tile drains in Rondeau Bay may be more adequately captured in future research through direct drain and water table monitoring, or hydrograph separation modelling (e.g., Cey et al., 1998).

3.5.2 Sediment Delivery

Rainfall inputs and runoff generation resulted in increased sediment entrainment at the studied site. This was evidenced by the positive relationship between discharge and SSC (Table 3.2). The estimated watershed denudation rate of 0.13 t ha^{-1} over the monitored period was considered low. For example in Canada, denudation rates below 6 t $ha^{-1}yr^{-1}$ are generally defined as having very slight to no erosion potential (Wall et al., 2002). This is because 6 t ha^{-1} yr^{-1} is the approximate rate in which most Canadian soils form through natural processes (Wall et al., 2002). However, the 0.13 t ha^{-1} is valid for the growing season and does not include potential sediment yield contributions corresponding to the spring runoff. As a result, the 0.13 t ha^{-1} denudation rate is lower than a range reported by Gaynor and Findlay (1995), who reported soil losses between 0.26 to 0.56 t ha^{-1} yr^{-1} for multiple no-till field plots between 1988-1990. In comparison, 1.6 to 2.4 times greater sediment yields were observed from conventionally-tilled fields during the study period (Gaynor and Findlay, 1995). The field plots were situated in close proximity to the Rondeau Bay study site, and were similarly underlain with a silty clay loam. Based on Gaynor and Findlay's (1995) findings, it is expected that no-till operations were also a sediment export control at the Rondeau Bay study site.

Variations in SSC and particle grain size were observed at the monthly and event scale throughout the monitoring period, and corresponded to rises in discharge and sediment source availability. The extreme July 19th event caused a temporary change in the suspended sediment response seen in the watershed, which was independent of discharge. For example, water samples were relatively decreased in suspended sediment and there was a notable increase in fine particle abundance for approximately one month following the event (Figure 3.6; Table 3.3). The changes in suspended sediment after July 19th were not related to crop maturity, or increasing riparian density, which could trap entrained sediment and reduce sample SSC (e.g., Steegen et al., 2000). This is because the change was only temporary, as sample SSCs increased (e.g., >10 mg L^{-1}) about one month following the event and fine particle abundance abruptly decreased at all monitoring stations by 20-30% despite increases in vegetative cover. The temporary change in suspended sediment potentially resulted from sediment redistribution within the stream channel, caused by high flow conditions during the July 19th event. In-channel sediment redistribution was evidenced by the burial of in-stream instruments, which were initially suspended 5 cm above the bed, in approximately 10 cm of sediment. Mobilized sediment often reflects the character of the eroded source material (Walling & Moorehead, 1989). As such, the newly redistributed sediment layer was fine in nature, and increased sample fine particle abundance. The sediment layer potentially derived from the channel banks, as evidenced by event-scale sediment hysteresis and newly developed scours at each monitoring station after July 19th. The contribution from a new sediment source, but relatively close source, such as the channel banks, helps explain the abrupt change in suspended sediment character and concentration. Another explanation is that the sediment redistribution caused aggregated particles to be broken up. Particle disaggregation would increase fine particle abundance within subsequent water samples (Slattery & Burt, 1997; Walling & Moorehead, 1989).

The potential for in-channel contributions at the Rondeau Bay study site was emphasized by event-scale clockwise sediment hysteresis. . During monitored rainfall events, the highest SSCs did not coincide with the event hydrograph peak and a clockwise hysteresis loop was observed, which suggests that erodible particles were entrained by the first flush of water (e.g., Klein, 1984; Steegen et al., 2000; Williams, 1989). A clockwise loop further indicates that contributing sediment sources are from the channel bed, banks, or other quick access sources such as tile drains (Klein et al., 1984; Williams, 1989). The primary reason is that transported sediment reaches the sampling area quickly, reducing the likelihood for deposition (Williams, 1989). The clockwise pattern further indicates that contributing sources were exhausted over the course of the rainfall event, as evidenced by the reduction in SSC prior to the discharge peak (Klein, 1984; Williams, 1989). Therefore, the clockwise hysteresis pattern observed support in-channel contributions (Figure 3.7). In addition, field surveys indicated that the channel is a major sediment source. Visible un-vegetated bank incisions lined the monitored reach (Figure 3.9), often extending to 2 m in height. Other researchers in Southwestern Ontario note the potential for in-channel source contributions. For example, Culley and Bolton (1983) estimated in-channel contributions at ~0.29 t ha^{-1} yr^{-1} in a nearby agricultural watershed. For comparison, recall the total estimated yield from the Rondeau Bay site was ~0.13 t ha^{-1} over a 6-month period. Consequently, in-channel sources may constitute large portions of the total sediment yield from the watershed at Rondeau Bay, as was observed at the Culley and Bolton (1983) field site.

There are potential contributions from other sources to consider, in addition to in-channel sources. For example, it is possible that tile drains contribute major sediment quantities to the overall yield, given that they contribute water to the stream (see section 3.4.1). If tile drains indeed respond quickly to rainfall inputs and sustain flow for longer periods, suspended sediment transported in tile drains may contribute to the sediment hysteresis loop observed during runoff events (Figure 3.7). For example, channel-based material that was exhausted by a storm event is recharged by tile drain contributions during the inter-storm period. By continually re-supplying the channel with sediment the event clockwise hysteresis (e.g., source exhaustion) pattern recurs during subsequent events. Multiple studies have reported relatively high sediment yields from tile drains. For example, Culley and Bolton (1983) reported that tile drainage accounted for at least 50% of the total sediment yield at their site between 1976-1977. However, the monitored fields were conventionally tilled, and likely produced more field-based sediment contributions compared to Rondeau Bay, where the fields were not tilled. Gaynor and Findlay (1995) reported tile drain-based sediment contributions at 44 - 65% for no-till conditions, in their study, which supports the possibility that similar suspended sediment quantities were delivered from tile drains at Rondeau Bay.

3.5.3 Nutrient Loading

Nutrient transfer was related to suspended sediment transfer within the studied watershed. This was evidenced by the positive correlation between SSC and Phosphorus ($R^2 = 0.86$) and Orthophosphate ($R^2 = 0.75$; Table 3.2). Other studies reported a similar association between SSC, and Phosphorus forms at other agricultural watersheds. For example, Culley and Bolton (1983), Hunter and Walton (2008), Poirier et al. (2009), Sharpley et al. (1992), and Steegen et al. (2001) report a positive agreement between SSC and total Phosphorus concentration ($R^2 = 0.81$, 0.94, 0.86, 0.84 and 0.48, respectively; $p < 0.01$). The predicted Orthophosphate yield of 0.8 kg ha^{-1} is near the 1-2 kg ha^{-1} yr^{-1} range reported by Gaynor and Findlay (1995) for other Southern Ontario no-till fields. Individual sample Phosphorus and Orthophosphate concentrations from Rondeau Bay were also within the 0.01-3.3 mg L^{-1} range reported by Culley and Bolton (1983) in a nearby watershed. As such, Ontario Provincial Water Quality Guidelines for Phosphorus (< 0.03 mg L^{-1}) were regularly exceeded throughout the monitoring periods in all three Southern Ontario watersheds (e.g., Rondeau Bay; Culley & Bolton, 1983; and Gaynor & Findlay, 1995). The Phosphorus guideline was exceeded by two orders of magnitude during storm events at the Rondeau Bay site. These findings suggest that Phosphorus loading occurred despite low sediment yields associated with no-till operations. Variations in Nitrogen content were not explained well by variations in SSC ($R^2 = 0.06$; Table 3.2). This is because sediment is not a primary N transport mechanism (Carpenter et al., 1998; Follett & Delgado, 2002). The limited range in SSC and N over the study period likely contributed to the poor relationship. For example, Hunter and Walton (2008) reported a strong positive relationship correlation (R^2 = 0.88), though with sampled SSCs ranging upwards of 1200 mg L^{-1}. In comparison, the highest recorded SSC at Rondeau was 406 mg L^{-1}. Similar to Gentry et al. (2007), elevated Nitrogen levels (e.g., > 20 mg L^{-1}) were reported during storm events. Although no guidelines for total Nitrogen have been established in Ontario, less than 10% of agricultural watersheds across the US reported average N levels greater than 10 mg L^{-1} during normal flow conditions (EPA, 2002). Of the 63 samples, 23 sample N concentrations in excess of 10 mg L^{-1} were observed during the monitoring period in Rondeau Bay.

A second discrepancy from the literature, in addition to the weak SSC-Nitrogen relationship, was that no significant relationship (e.g., $p > 0.05$) existed between fine particle abundance and nutrient concentration (Phosphorus, Orthophosphate, and Nitrogen). The fine particle - nutrient loading relationship was skewed during instances of increased flow (e.g., event flow), where the corresponding increase in SSC and nutrient content were not met with increases in fine particle abundance. However, studies citing a strong relationship between fine particle abundance and nutrient content included nutrient concentration ranges that were orders of magnitude higher than ranges observed at the Rondeau Bay site (e.g., Quinton et al., 2001).

In summary, stream nutrient levels remained above provincial guidelines despite low sediment yields from the monitored stream at Rondeau Bay. It is not uncommon for non-tilled fields to be characterized by increased nutrient loads relative to conventional-tillage (e.g., Gaynor & Findlay, 1995; Sharpley, 2003). By avoiding tillage, nutrients can avoid being mixed into the soil, thereby increasing the potential for losses in overland flow and tile drains

(Sharpley, 2003). It is difficult to deduce whether no-till operations contributed to increased nutrient loading at the Rondeau Bay study site, as the relationship between no-till and nutrient loading varies with location (McDowell & McGregor, 1980). Multiple studies report increased nutrient concentrations deriving from tile drains (e.g., Gaynor and Findlay, 1995; Sims et al., 1998), in addition to non-tilled fields. This is because tile drains offer a relatively short pathway to the draining stream, reducing the likelihood for root nutrient uptake (Sharpley, 2003). As such, there is potential for increased nutrient loading from tile drains at Rondeau Bay, given the noted potential for tile drains to contribute high quantities of water.

3.6 Conclusions

This study evaluated the hydrological, sedimentological, and nutrient loading response to summer rainfall inputs in a small agricultural watershed in Southern Ontario. Various factors controlling the watershed response were identified and are summarized here. The research demonstrated that runoff generation caused by rainfall events leads to sediment and nutrient mobilization. A threshold rainfall input of ~10 mm day^{-1} was needed to elicit a response in the hydrograph. Variations in runoff and streamflow generation between monitoring stations was controlled mainly by tile drain presence. For example, the reach segment characterized by a high tile drain density (e.g., Talbot to Eds station) corresponded with shorter hydrograph lag-to-peak durations and greater flow contributions per unit area from rainfall inputs. In contrast, monitoring stations characterized by a lower tile drain density responded more slowly overall. The varying hydrograph responses suggest that tile drains contributed event flow to the stream, in addition to delayed baseflow. As such, tile drains are a potential pathway for sediment and nutrient transfer because they connect arable fields directly to the draining stream. The need to better understand the role of tile drains in flow contribution, and sediment and nutrient transfer is emphasized in Southern Ontario, where tile drain implementations are becoming increasingly popular (Stats-Canada, 2007).

The estimated sediment yield from the studied watershed over the monitoring period was considered low (0.13 t ha^{-1} over 6 months). The low sediment yield was likely influenced by no-till practices on the surrounding fields. The yield is low relative to estimated yields from nearby non-tilled watersheds because the 0.13 t ha^{-1} does not include sediment transfer data from spring runoff. The July 19^{th} event (~92 mm) was responsible for a temporary shift in suspended sediment transport within the watershed. For example, post-July 19^{th} water samples were lower in SSC and fine particle abundance increased, for one month. Based on this observation, high magnitude rainfall events have a lasting impact on sediment and nutrient transfer in watersheds. This is important in Southern Ontario, where studies indicate increasing trends in storm frequency and magnitude (Bruce et al., 2006). The positive event-scale sediment hysteresis, which was observed for sufficiently monitored events, suggested that sediment was derived from quick access sources (e.g., in-channel, tile drains). As such, rainfall events potentially exhausted in-channel sediment sources, and tile drains resupplied the channel with sediment during low-flow conditions. Water samples analyzed for Phosphorus, Orthophosphate, and Nitrogen content exceeded Ontario Provincial Water Quality Guidelines. The positive relationship between SSC, Phosphorus and Orthophosphate, confirmed that Phosphorus loading was sediment assisted. Therefore, high nutrient loads occurred in the monitored stream, despite land management efforts to prevent sediment and nutrient transfer (e.g., no-till).

The collection of high frequency hydrological, sedimentological, and nutrient export data is important for the calibration and validation of environmental soil loss and pollutant transfer models (e.g., WEPP, CREAMS), in addition to the general contribution of knowledge to the field. In order to function effectively, remedial techniques such as environmental models, and Best Management Practices require high-resolution spatial and temporal data. This study contributed directly to that need. The collected data will thus aid governing bodies to make informed decisions on soil erosion and nonpoint source pollution policies and regulations.

Tables and Figures

Table 3.1: Rainfall event summary, antecedent soil moisture conditions, and flow generation at the monitoring stations. Flow specific to each station was estimated by subtracting flow contributions from upstream stations and dividing the contributing area.

Event summary	24-hour rainfall (mm)	5-day antecedent rainfall (mm)	Talbot flow (mm)	Eds flow (mm)	Front flow (mm)
May 28	54.8	2.8	43	18	6
June 13	33.6	8.8	37	10	4
June 18	20.0	35.6	60	15	7
June 27	22.4	7.8	70	16	6
July 7*	59.8*	11.4	105	25	12
July 19**	92.4	3.0	N/A	N/A	21
August 1	41.0	6.4	33	9	4
August 13	19.4	0.0	41	12	5
September 20	48.4	6.2	84	17	10
October 6	25.6	1.8	48	10	5

* Multiple event peaks, total rainfall was summed for all events.
** Missing data due to sensor flooding

Table 3.2: Regression equations for the relationship between discharge (Q), suspended sediment concentration (SSC), Phosphorus and Orthophosphate and Nitrogen concentration.

n	Equation	R^2	P-value
87	$SSC = 687 \times Q - 1.53$	0.73	<0.001
63	$P_{concentration} = 0.007 \times SSC + 0.267$	0.86	<0.001
63	$PO_{4\ concentration} = 0.004 \times SSC + 0.199$	0.75	<0.001
63	$N_{concentration} = 0.035 \times SSC + 8.00$	0.06	>0.05

Table 3.3: Fine particle abundance in suspended sediment collected from sediment traps.

Date retrieved	Talbot station - Trap fine particle (% < 21µm)	Front station - Trap fine particle (% < 21µm)
May 16	49	58
May 31	45	57
July 31	68	71
Sept 25	42	54

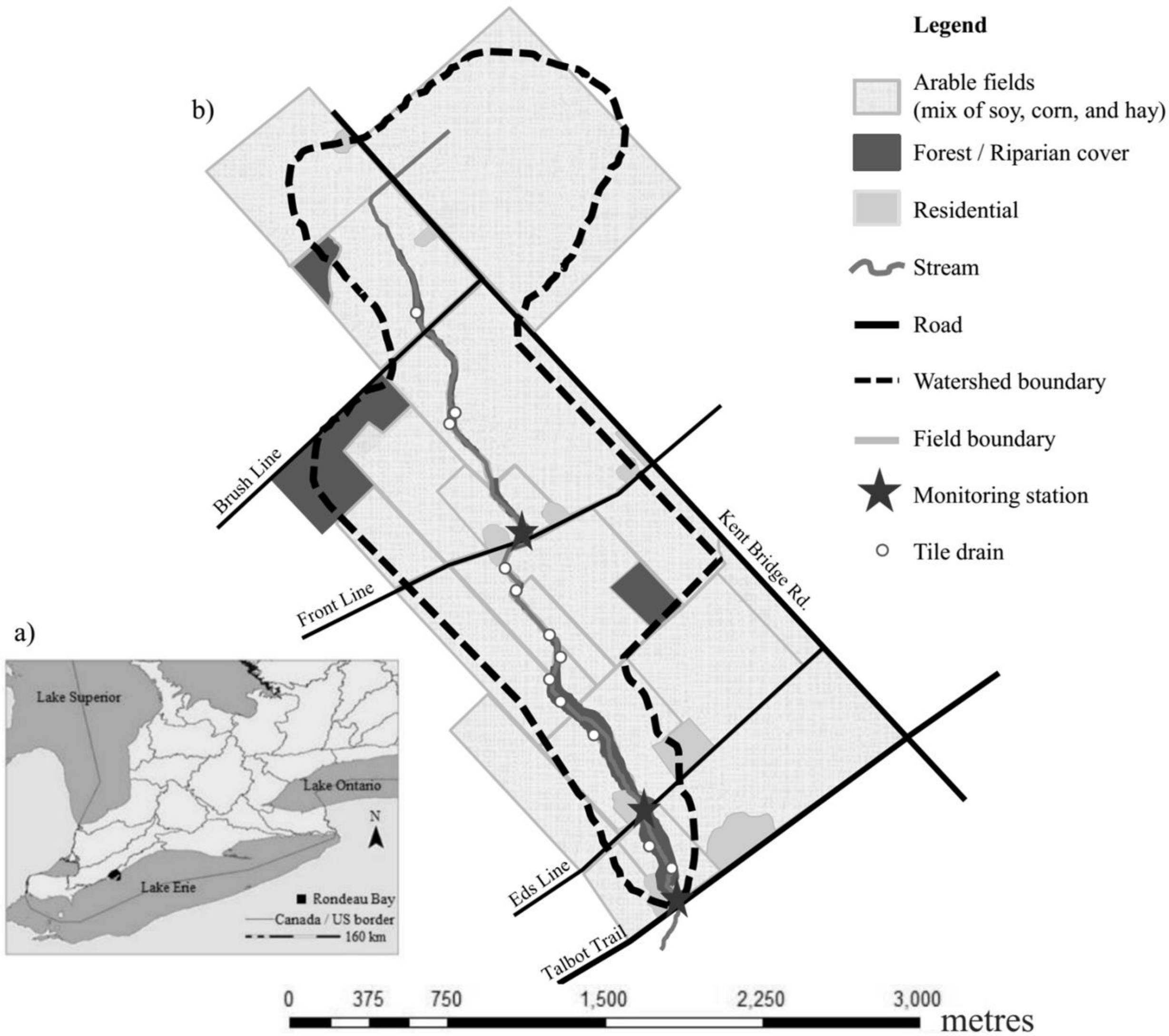


Figure 3.1: (a) Study site along the north shore of Lake Erie, near Blenheim, Ontario; (b) Study site overview. Water network delineation adapted from *Minor Water Lines* from DMTI spatial Inc. 2012.

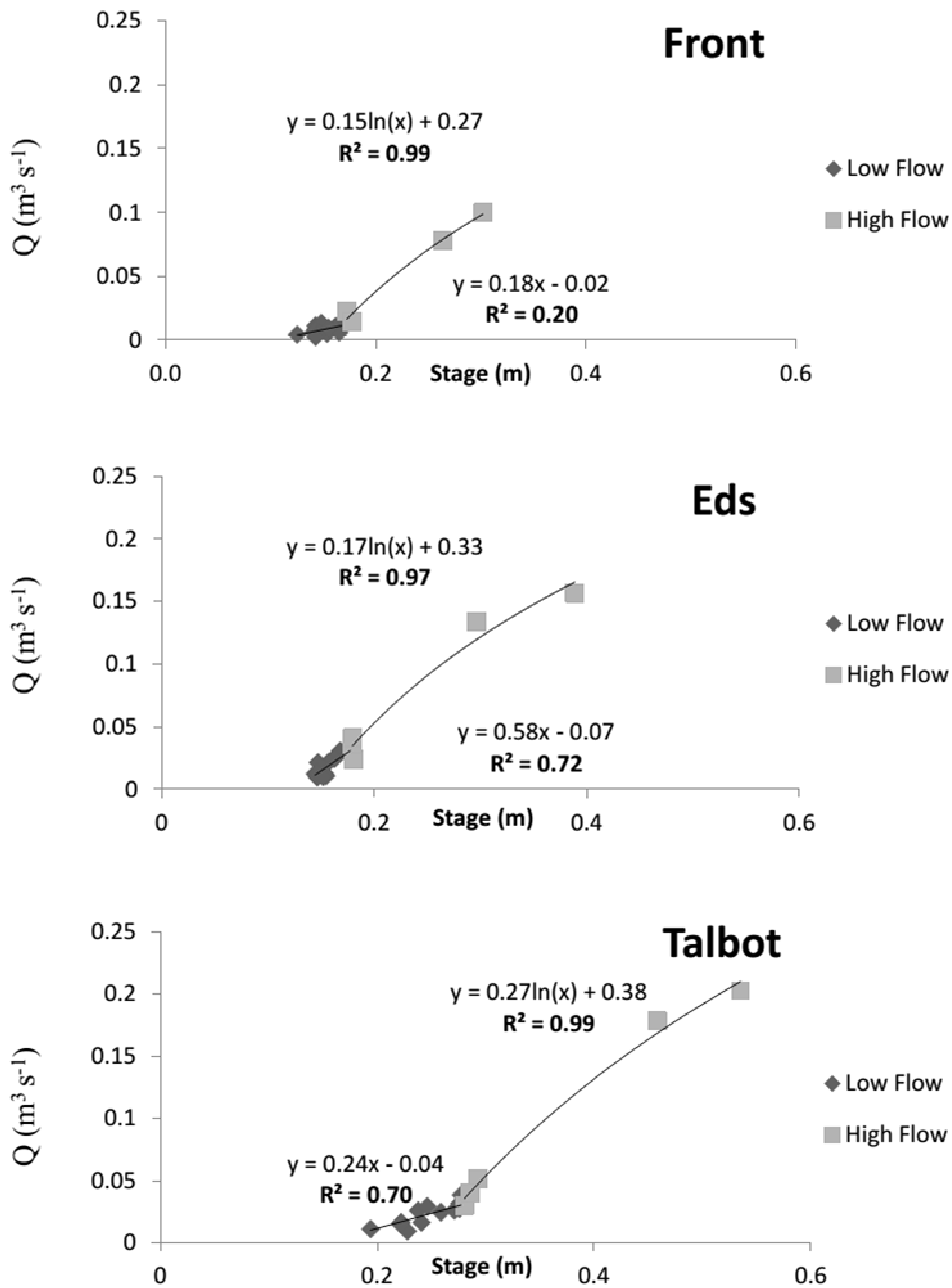


Figure 3.2: Stage - discharge rating curves for each gauging station, from upstream (Front) to downstream (Talbot). High Flow series (squares) indicates above bankfull conditions, Low Flow series (diamonds) indicates below bankfull conditions.

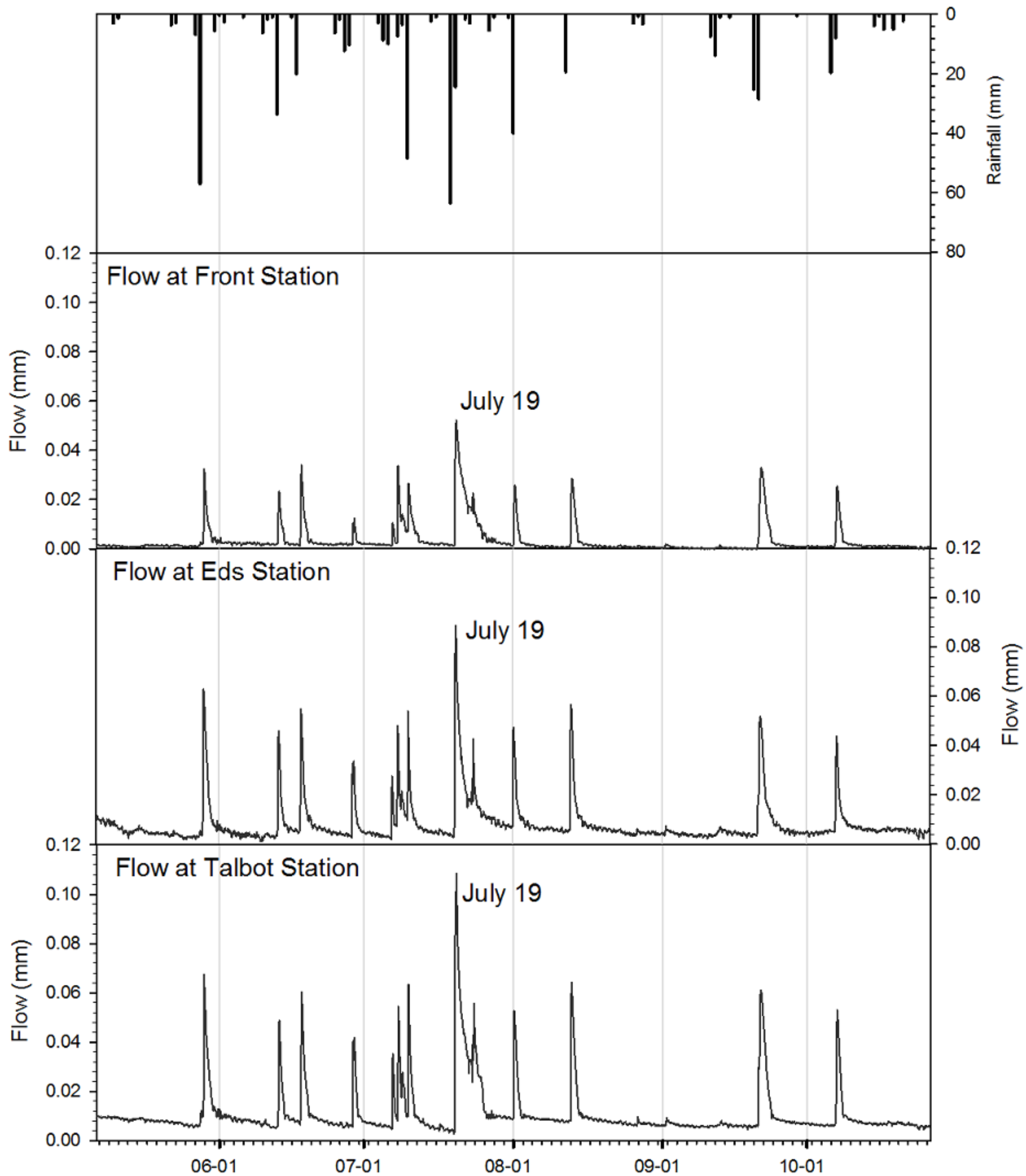


Figure 3.3: Precipitation and discharge over the field season. Precipitation is shown on the upper x-axis. The largest peak denotes the July 19th event. The dotted line at Talbot station July 23 - 25 accounts for lost data due to sensor flooding.

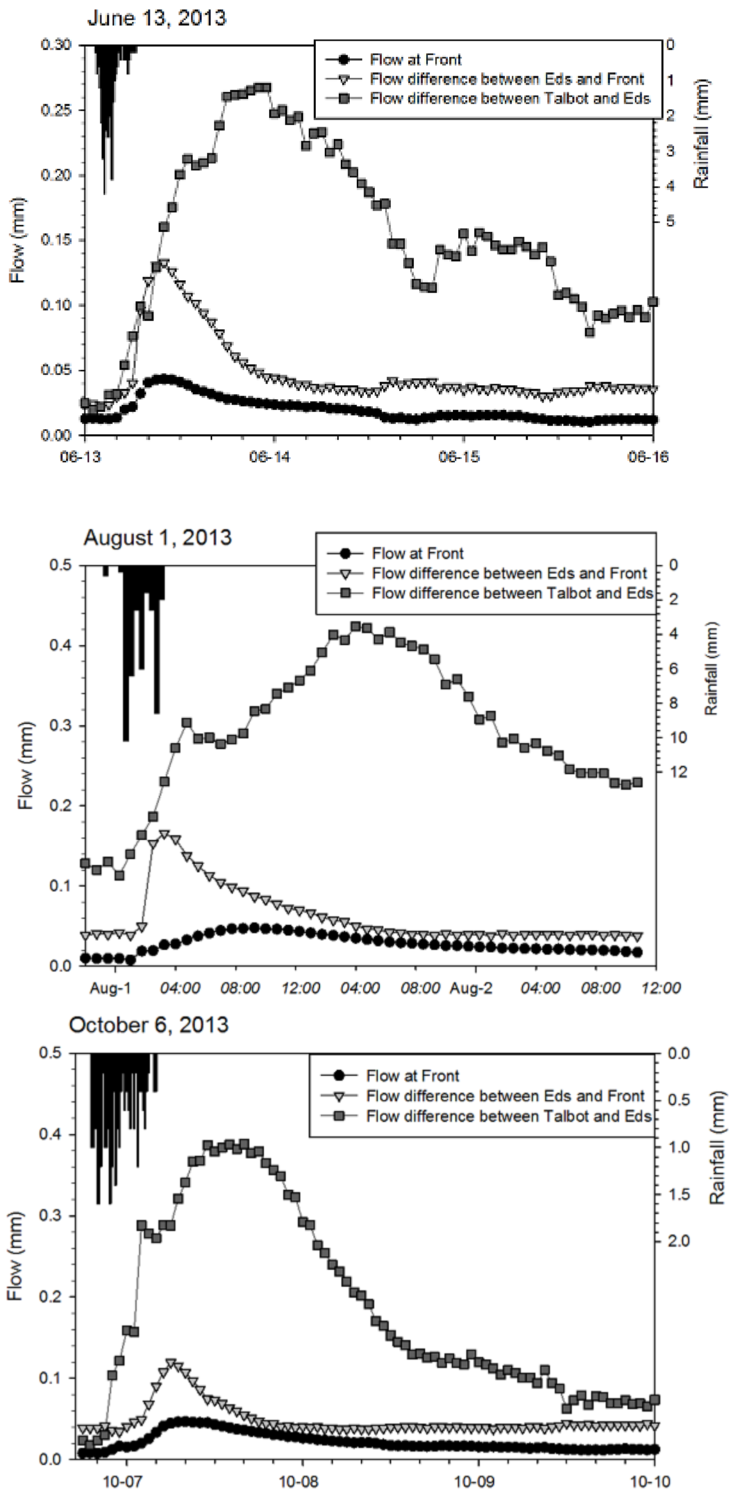


Figure 3.4: Precipitation and discharge for Front (circles), Eds (triangles), and Talbot (squares) station during the June 13th, August 1st, and October 6th rainfall events.

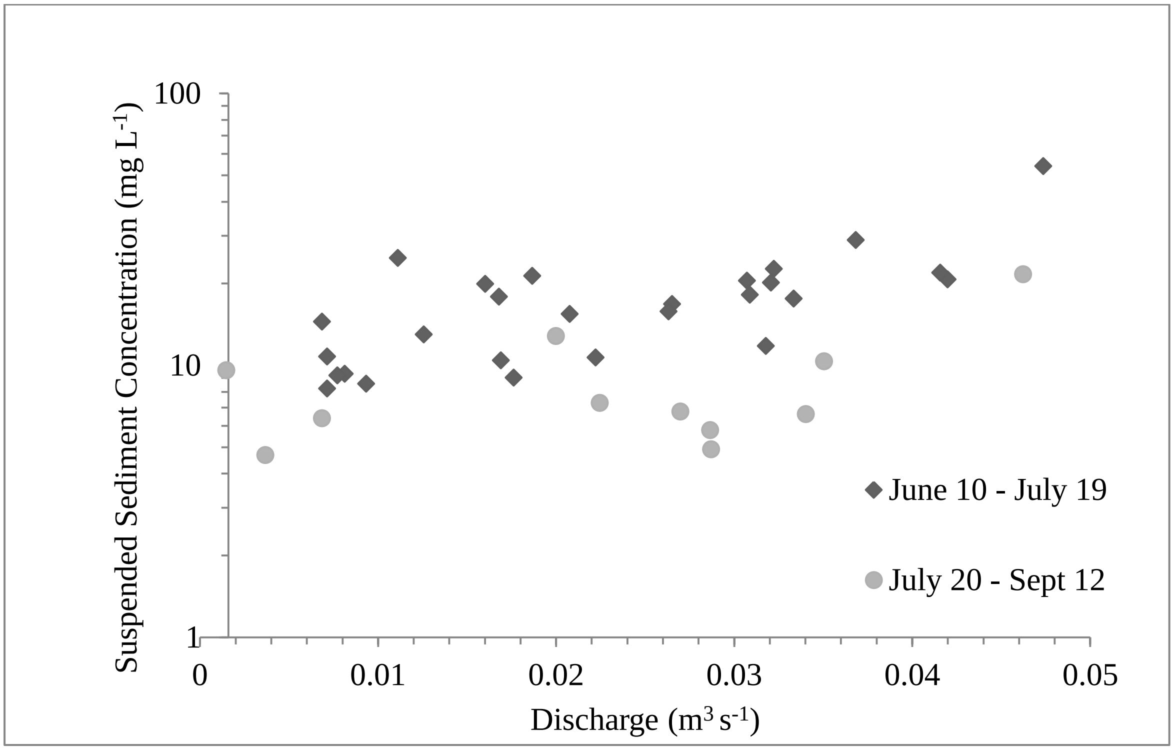


Figure 3.5: SSCs leading up to (diamonds) and following (circles) the July 19th event, showing an apparent reduction in concentration relative to discharge.

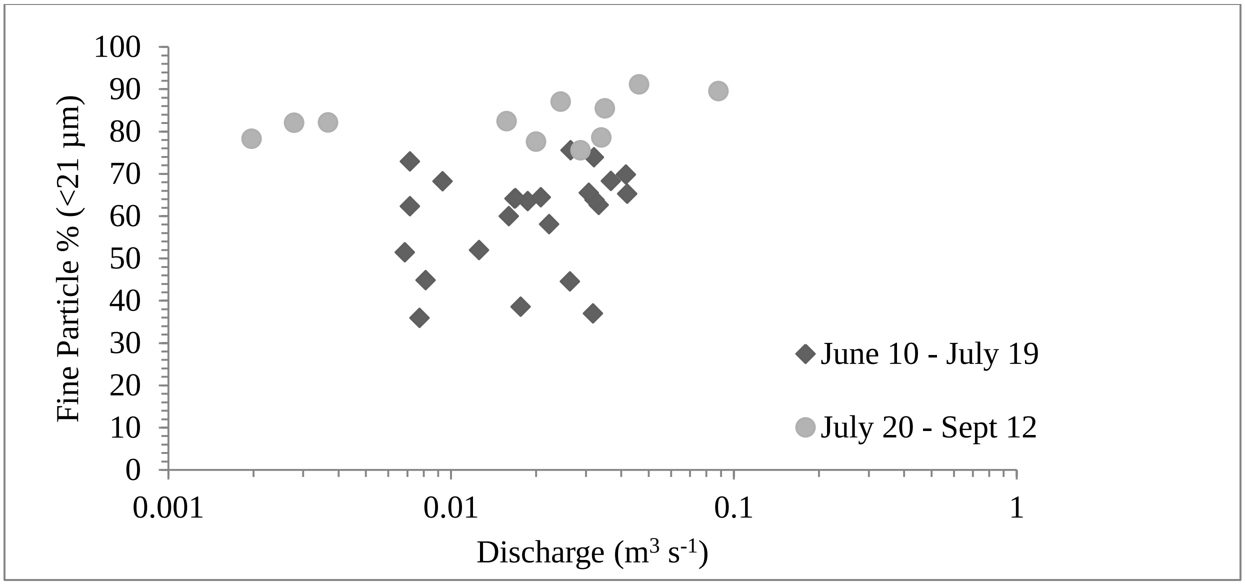


Figure 3.6: Water sample fine particle abundance increase before (diamonds) and after (circles) the extreme July 19th event.

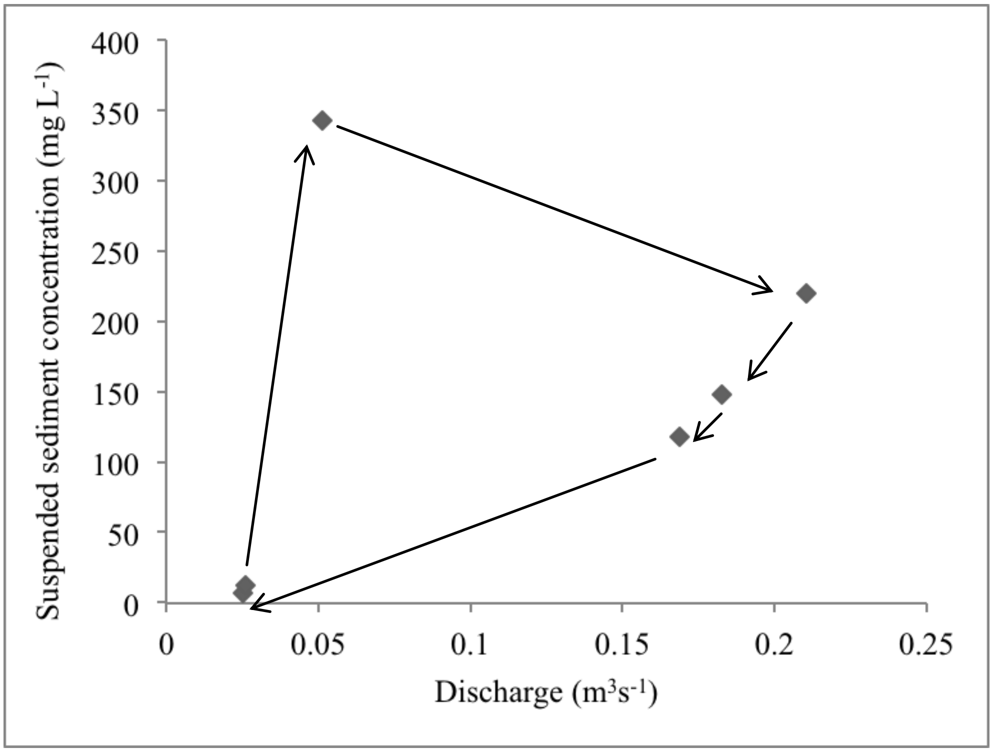


Figure 3.7: Clockwise hysteresis pattern exhibited on October 6th at Talbot station. The clockwise loop was apparent at Talbot, Eds and Front station during this rainfall event.

Figure 3.8: Observed flow from tile drains on August 22nd between Front and Eds stations, following a two-week no-rainfall period.

Figure 3.9: Bank incision near Eds station, a metre stick on the left side is shown for scale.

Chapter 4. Conclusion

This thesis summarized a comprehensive study on the hydrology, geomorphology, and nutrient dynamics in a small agricultural watershed in Southwestern Ontario. The response of these factors to summer rainfall events was evaluated over a 6 month monitoring period. The study findings and have important implications for future research of agricultural runoff. The major results, discussion points, and contributions are summarized below:

- Streamflow was generated by rainfall inputs, and was impacted by tile drain presence and riparian vegetation. Tile drains were considered to respond quickly to rainfall inputs, and shortened the average streamflow response time at stations characterized by increased tile drain presence. However, field observations also supported delayed flow tile drain contributions during prolonged periods with no recorded rainfall. Thus, the study findings reinforce the need to better understand the factors controlling the tile drain response to rainfall inputs. It is suggested that future research monitor the tile drains and water table directly, to provide insight into the effect of subsurface antecedent moisture conditions on tile drain flow response. Tile drain monitoring is particularly important in Southern Ontario, in addition to Rondeau Bay, because tile drain implementation in agricultural fields are increasing (Stats-Canada, 2007; Denault et al., 2010).
- The discharge - suspended sediment concentration relationship (SSC) was fitted with a linear sediment rating curve, and corresponded to a sediment yield of 0.13 t ha^{-1}. Though, linear trends generally do not fully capture suspended sediment variations during rainfall events, where suspended sediment concentration may peak before or after the event hydrograph peak. The non-linearity between discharge and SSC is caused by sediment hysteresis and is more accurately represented by separate rising and falling limb

equations if sufficient sampling occurs during rainfall events (e.g., Steegen et al., 2000). The total estimated suspended sediment yield from the watershed was considered low, compared to the natural soil formation rate (Walling et al., 2002). The no-till effect on reducing sediment yields from agricultural fields is well known in the literature (Gaynor & Findlay, 1995; Verhulst, 2007). It is expected that no-till operations at Rondeau Bay contributed to the observed low sediment yield, as conventionally-tilled fields are typically characterized by larger losses (e.g., Culley & Bolton, 1983; Gaynor & Findlay, 1995). The no-till effect on sediment mobilization is important in the Great Lakes region because the number of farmers reporting no-till practices has tripled over the last two decades (Stats-Canada, 2007).

- There was a ~1 month decrease in SSC and increase in suspended sediment fine particle abundance following a high magnitude rainfall event. This suggests that extreme events impacted sediment source availability and transfer dynamics in the watershed, which is important because studies indicate increasing trends in rainfall event frequency and occurrence in Southern Ontario (Bruce et al., 2006). The post July 19th change in suspended sediment was attributed to in-channel sources (e.g., channel bed and banks). In-channel sources were evidenced by field observations of sediment redistribution on the channel bed and scoured banks, in addition to event-scale clockwise sediment hysteresis.
- Phosphorus and Orthophosphate were positively correlated with SSC. Water sample nutrient concentrations exceeded provincial water quality guidelines, which suggests that land management practices intended to reduce sediment loss from agricultural fields (e.g., no-till, tile drains) do not mitigate nutrient loading. No-till is occasionally considered to increase nutrient losses in surface runoff from fields because it prevents nutrient mixing

into the soil (Gaynor & Findlay, 1995; Sharpley, 2003). As such, nutrients are potentially sourced from tile drains or from in-channel sources along with SSC.

The knowledge gained from this study and similar studies has implications for watershed management. The study highlighted three areas where current knowledge needs to be built upon by future researchers and watershed managers. Firstly, by monitoring flow and suspended sediment regularly throughout the season it was revealed that high magnitude events have a temporary impact on the character and concentration of suspended sediment, in addition to constituting large quantities of the overall sediment yield. It is suggested that the change in suspended sediment occurred as a result of source redistribution or particle disaggregation. However, there is little information available in the literature to support this suggestion or provide alternative explanation for the phenomenon. This is because researchers often focus on monitoring suspended sediment transfer during individual events or high flow conditions, instead of sampling regularly throughout events and baseflow conditions. As a result, short-term changes in sediment transfer and sediment source contributions from rainfall events are potentially overlooked. Secondly, this study demonstrated that potentially high quantities of sediment and nutrients are derived from in-channel sources in agricultural streams. This was implied by field observations of channel erosion (e.g., bank failure, channel incisions) and clockwise sediment hysteresis patterns during rainfall events. As such, there is a need to identify and account for channel bank and bed sources of sediment and nutrients. Future research needs to address how to mitigate nutrient transfer from channel sources, in addition to nearby agricultural fields. Finally, this study identified a knowledge gap associated with the influence of tile drains and no-till practices on sediment and nutrient transfer dynamics. In general, tile drains and no-till practices are implemented for soil and water conservation purposes (Verhulst et al., 2007). However, little is known as to how tile drains behave hydrologically in different settings and in conjunction with other management practices (e.g., no-till). There are varying claims in the literature based on whether or not tile drains constitute large quantities of flow, or contribute to event hydrograph peaks (Robinson, 1989; Sims et al., 1998). Furthermore, few studies have addressed nutrient transfer within tile drains from non-tilled fields, where surface nutrient accumulation is potentially increased (Sharpley, 2003). It is therefore difficult to predict nutrient transfer from many Southern Ontario watersheds where tile drain and no-till practices are common (Denault et al., 2010; Stats-Canada, 2007).

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