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THE EFFECT OF WATER TEMPERATURE ON IN-STREAM SEDIMENT CONCENTRATION AND TRANSPORT RATE

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THE EFFECT OF WATER TEMPERATURE ON IN-STREAM SEDIMENT CONCENTRATION AND TRANSPORT RATE

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ABSTRACT

THE EFFECT OF WATER TEMPERATURE ON IN-STREAM SEDIMENT CONCENTRATION AND TRANSPORT RATE

Global climate change may result in rising temperatures. As a result, ecological health and the human use of rivers may be impacted. The hydrologic cycle, watershed hydrology, and in-stream hydraulics are dynamic systems, influenced by human activities, natural events, and climate. Although known drivers like precipitation and stream velocity govern sediment processes, the effect of water temperature on sediment transport remains unclear. In-stream sediment movement could lead to blocked harbors, flooding, and degradation of vulnerable fish habitat. To better understand how fluctuations in water temperature affect sediment dynamics, six transport models were analyzed on the Niobrara River, with water temperatures ranging 1° to 40° C. The results indicate that as water warms sediment transport decreases, according to an inverse, non-linear law, with the highest reduction at colder water temperatures. The results given here can help predict changes in sediment transport for rivers with similar characteristics at various water temperatures.

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CHAPTER 1. INTRODUCTION AND BACKGROUND

Watershed projects offer roughly $ 2.2 billion in annual benefits for an estimated 47 million Americans and include public safety measures such as flood mitigation and water quality, as well as improvements for erosion control, recreation, navigation, and wildlife habitat (USDA, 2015). However, are these projects beneficial and sustainable for future generations and ecosystems? People of the United States and the world are making pivotal choices about development and the environment. Documenting and understanding how these important decisions change hydrology and the course of the Earth's processes, are essential to all forms of life (NRC, 1999). Human and ecosystem welfare are directly connected to the environment; and without reliable research about changes in the hydrologic cycles, climate structure, ecological systems, and the soil/nutrient resources, strategies to protect human and environmental interests cannot be developed and sustained (NRC, 1999).

1.1 Hydrology-Watershed-River Interaction

The interaction between the hydrologic cycle, the watershed, and river behavior is complex. As precipitation falls and impacts the earth, the water either infiltrates or runs off, depending on the rate of precipitation, the soil moisture, and soil type (Aksoy, 2005; Baffaut et al., 2013). Infiltrating water replenishes the groundwater supply (R.E., 1933) while runoff travels overland (Li et al., 2011).

Hillslope erosion occurs when precipitation impacts the ground and dislodges the soil particles, transporting them downstream to either deposit lower in the watershed (Aksoy, 2005; Reusser et al., 2015) or into a stream/river (Aksoy, 2005). Subsequent to entering a river, the flow and sediment influence the conditions in the watercourse. A river will work to achieve stable conditions with a specified supply of water and sediment, by adjusting its geometry and velocity (Julien, 1995). Once water enters the river, the velocity and flow depth will increase. A faster velocity will increase the in-stream potential to **transport sediment** both in suspension and along the bed (Chiodi F., 2014). The balance between the amount of water entering the river and the flow downstream can cause the flow depth to rise above the riverbanks and result in flooding (García-Ruiz et al., 2008). If the rate of sediment entering the river exceeds the sediment transport capacity of the river to transport the sediment, then the riverbed aggrades and could lead to flooding (C., 2005; K.R., 1995). Conversely, when the rate of sediment entering the river is less than the sediment transport potential of the river, the possibility for bed degradation and blocked harbors can occur (J.L., 2005).

Flow and sediment behavior are also important for fish survival (Cotton et al., 2006; Dudley, 2007; J.L., 2005). A river's dynamic behavior will alternate between sediment deposition and erosive sediment states, generating temporal variability that creates healthy and resilient aquatic habitats (G.H., 1995). On the other hand, excessive suspended sediment can settle into the bed particles and clog interstitial pore spaces, suffocating fish eggs that need oxygen to thrive (Dudley, 2007; Suttle, 2004). Just as detrimental to fish survival is excessive movement of the bed sediment, which physically damages the fish eggs (Wenger et al., 2011) and benthic organisms needed for fish food (Dudley, 2007).

Natural events and human activities have altered this interaction in numerous ways (Nilsson C., 2005; Walling, 2006). Natural cycles like wildfires (Moody, 1996) and landslides disturb vegetation. Development of the watershed with impervious surfaces such as parking lots and roofs, mining, channelization of rivers, timber harvesting, and agriculture (Reusser et al., 2015; Suttle, 2004) interrupt the natural hydrologic cycle. Through these various ways additional water and pollutants are added to the local stream network, thereby adversely affecting fish and the ecology (EPA, 2014; G.H., 1995).

The effect of **global climate change** (GCC) may be superimposed upon this tapestry of watersheds, hydrology, and stream/river flow. The effects of climate change is uncertain and rising temperatures is a current research topic with some degree of uncertainty (Chaplot, 2007; Labat, 2004). GCC could increase the amount of precipitation in some areas of the globe, while reducing it in others (Labat, 2004). Rising temperatures may result in increased evaporation from lakes, oceans, and from the soil (Labat, 2004; T.L., 1988). Due to a warmer climate, increased plant uptake could also withdraw moisture from the soil (Bosch, 2014). Increased water temperature also affects fish and aquatic life habitat (D.J. et al., 2010; Whitehead, 2009). Additionally, rising temperatures may affect the rate at which sediment flows in streams and rivers (Hong, 1984; Li et al., 2011; Straub, 1958). This effect of water temperature on sediment transport potential is unclear and is the focus of this current study. Although the focus of this study is specific to the effect of water temperature on instream sediment outcomes, a few causes of sediment supply from upland watershed sources are highlighted here.

1.1.1 Hillslope Erosion

Surface runoff is the flow of water that occurs over impervious surfaces, or when the rainfall rate is greater than the soil infiltration rate or antecedent moisture conditions (Li et al., 2011). Sediment motion via land erosion is an interaction between land use, weather, soil, topography and management conditions (Shrestha, 2013) and is a function of the flow of water, soil properties, and the land characteristics (Aksoy, 2005). Overland soil erosion occurs by way of soil detachment, via raindrop impact and/or runoff, and by means of land topography (Aksoy, 2005).

In recent decades, natural events, human activities, and global climate change have altered surface runoff and increased the sediment load in rivers all over the world (Nilsson C., 2005; Walling, 2006). Measuring sediment loads is complex because there is not an exact point source. There are natural rates of sediment supply to rivers (Reusser et al., 2015), impaired watersheds that contribute to sediment loads (J.L., 2005), and various in-stream processes like bank erosion (J.L., 2005).

1.1.2 Human Activity

The world's human population increased from 2.5 billion to more than 6 billon people between 1950 and 2000. Although humans have been altering land cover for centuries, human activities such as energy use and land use change has accelerated rapidly over the past sixty years (NRC, 1999). Sediment flux into and out of streams/rivers, although a natural process, has been intensified by humans (Reusser et al., 2015; Suttle, 2004). Land use change, such as timber harvesting (Curry et al., 2004; Reusser et al., 2015), mining, urbanization, particularly road construction (Suttle, 2004, Burns, 1972, Reid et al. 1981), and agriculture (Curry & MacNeill, 2004; Reusser et al., 2015) have the potential to increase sediment fluxes by interrupting the natural hydrologic cycle with impervious spaces and/or less vegetation. Much research demonstrates that these activities are causing more surface runoff, soil erosion, and sediment deposition in streams, causing negative effects on aquatic life like salmonid populations (Curry & MacNeill, 2004). However, Curry (2004) also points out potential benefits of responsible timber harvesting, such as enhanced light penetration and nutrient inputs, which increase productivity and growth of river biota.

Other human activities that contribute to erosion and sediment transport are alterations to river morphology through channel straightening, and removal of riparian vegetation (D.J. & al., 2010), flood plains, and wetlands (Whitehead, 2009). The construction of dams also alters hydrology and thus the sediment transport process, potentially threatening naturally evolved freshwater ecosystems (Dudley, 2007; Gardner et al., 2013). Once built in a river, dams reduce upstream flow and sediment particles settle out of suspension (Suttle, 2004). Over time, sediment builds up behind the dam. When a dam is removed, the trapped sediment is carried downstream. One example of the impacts is the world's largest dam removal project that started in late 2011 on the Elwha River in Washington State. This was a major sediment transport event, resulting in with over 3-million truck loads of sediment carried into the Strait of Juan deFuca (Nijhuis, 2014). Society may feel the impacts sooner, as the strait is a major shipping route for both the United States and Canada, but, implications to marine life may not be realized for years (Gardner et al., 2013).

1.1.3 Natural Events

Natural events, like wildfires, produce similar results to that of deforestation and mining where vegetation is either disturbed or removed, allowing for soil erosion and increased sediment in rivers and streams (Moody et al., 1996). Natural cycles contribute to both overland and in-stream sediment transport processes. For instance, a Taiwan typhoon documented on a hurricane science website (2010), turned a once lush hillside into a clear-cut hillside. Due to heavy rainfall and landslides, the exposed soil is highly vulnerable to erosion that could potentially lead to added sediment in rivers and streams.

1.1.4 Climate Change

Recent studies show an increasing trend in rainfall erosion throughout the United States due to an increase in the frequency of heavy rainfall events (Nearing, 2004; Whitehead, 2009). As rainfall intensity increases, sediment yields respond differently at river and watershed scales (Bosch, 2014). One study showed that in a river with increasing water depth and flow-rate, sediment concentration decreases.(cite?) Conversely, on the watershed, due to soil detachability capacity on land, sediment concentration was higher as rain intensified (citations). Some of the research is conflicting. For instance, although it is well known that increased precipitation intensity leads to high surface runoff velocity resulting in soil erosion, one study showed only one-fourth of the eroded sediment is delivered to waterbodies, while the remaining is deposited on the watershed along the way (Aksoy, 2005).

Ultimately all of these events will modify river discharge and in-stream sediment transport at some scale (Heglund, 2010). To better manage water resources in a changing environment, river managers must consider the potential effects of climate variability and human activities, and characterize how these changes affect sediment motion (Ficklin et al., 2014). Reusser (2015) highlights that prior to the 1980s there were no reliable techniques capable of quantifying pre-settlement rates of erosion over geologic time scales. As a result, there is an absence of baseline data to quantify the magnitude of erosion due to human activities, which is a critical component in sustainable land and water resource management. Although a few examples of watershed erosion have been mentioned here, this study does not consider sediment yields from the hillslope. Rather, the focus of this study zooms in to the sediment transport potential within the waterbody.

1.2 In-Stream Sediment Transport: Importance

As climate variability and intense rainfall events increase, sediment behavior will also change. Although it is important to forecast sediment outcomes from extreme weather events to determine the expected erosion and sedimentation (Ficklin et al., 2014), predicting sediment behavior in a river is one of the basic challenges faced in the science of sediment transport (D.L., 1994; Kharlamova et al., 2014; Murphy, 1985). An increase in sediment will alter water quality (S. N. Lane, 2006) which will, in turn, affect aquatic ecosystems (Heglund, 2010; Whitehead, 2009), potentially block shipping harbors (C., 2005; Ghobrial, 1987) and may increase flood risk (S. N. Lane, 2006).

1.2.1 Human Implications

Excessive sedimentation has the potential to block harbors (C., 2005). This widespread impact hinders shipping and may require dredging, which is both expensive and damaging to marine life of the area (Ghobrial, 1987). Another effect of sediment transport is extreme deposition in river channels which could lead to potential flooding (García-Ruiz et al., 2008), threatening public safety (S. N. Lane, 2006).

A local example of induced flooding due to excessive sediment deposition is a project in Au Train, Michigan. Residents reported trouble with flooding and contacted the Department of Natural Resources for help. During the summer of 2014, the Great Lakes Research Center at Michigan Tech was tasked with surveying the Lake Superior shoreline in order to better understand the sediment deposition and flow behavior (Meadows, 2014). The Au Train river mouth empties into Lake Superior just north of Highway 28; due to sediment deposition along the Lake Superior shoreline, ice dams form at the mouth of the river. During spring melt, the ice dam blocks the river outlet and causes flooding upstream.

1.2.2 Natural Impacts

Although thermal effects of climate change are primary survival concerns for aquatic species (D.J. & al., 2010), river flow and sediment behavior are also important**.** Ecological effects of sediment transport include degradation of diverse aquatic habitats for fish and other species (EPA, 2014; G.H., 1995), and alteration of their survival thresholds with respect to water quality (Stewart, 2014; Suttle, 2004). An increase of fine sediment will alter river ecosystems by smothering rearing habitats and lowland floodplains which shrink suitable aquatic habitats (Suttle, 2004). According to the National Marine Fisheries Service, twenty-six Pacific salmonid species are threatened (Suttle, 2004), in large part due to fine sediment deposition suffocating spawning and rearing habitat, and the food webs supporting them. However, research supporting this evidence is primarily laboratory work because during in-field experiments it is difficult to isolate the impacts of sediment from other physical factors (like velocity, temperature, water depth, river morphology) that influence aquatic performance (Suttle, 2004). Curry et al. (2004) reported different results from a field study on the population-level responses to sediment during early life in brook trout on Prince Edward Island. The study area landmass is roughly 20% potato row cropping, which is increasing sediment input into streams. The authors concluded sediment loads had little to no effect on brook trout populations, and in fact, the study demonstrated broader life-history tolerance.

Diverse habitats are created naturally by a river's dynamic spatial and seasonal patterns (Cotton et al., 2006; G.H., 1995). Variable flow regimes in upland streams create pool and riffle sequences and form natural meanders, supporting aquatic life (Whitehead, 2009). Subsequently, under these dynamic flow regimes new habitats are created (and disturbed) downstream. The deposition of sediment, or aggradation, forms floodplains and bars in the channel. These opposing and diverse processes create and maintain spawning gravel and rearing habitat for aquatic species (Kondolf, 2000). This natural progression by which rivers transport sediment is repeated, gradually eroding the riverbed, but also restocking material from upstream (Prothero, 1996).

Typically, as development near the waterfront grows, a river's natural tendency to change over time is restricted. Likewise, the species living in and around these environments are also constrained. As population grows and land use changes, surface runoff and soil erosion could intensify, which in turn adds turbidity in rivers, potentially threatening survival thresholds for native species (Chaplot, 2007; Davies-Colley, 2001). High suspended sediment concentrations limit light penetration and facilitate low oxygen content (K.R., 1995). Depending on the source, sediment can be a vehicle transporting nutrients (Cotton et al., 2006) and sorbed contaminants, from the water column to the river-bed and vice-versa, causing a broad range of environmental concerns (Davies-Colley, 2001; Shrestha, 2013). Consequently, to better understand the dispersion is important to understand the movement and deposition of sediment particles (K.R., 1995). This study will focus on one variable, water temperature, and the effect on sediment movement.

1.3 In-Stream Sediment Transport: Drivers

Sediment transport is related to the characteristics of river flow, the sediment, and the watershed basin (Colby, 1964). The relationship is complex and variables change based on flow and sediment regimes. The primary factors that govern particle motion, other than the properties of the fluid and sediment itself (Heglund, 2010; Kharlamova & Vlasak, 2014; Prothero et al., 1996), are the riverbed structure (roughness and slope) and the flow pattern (Laursen, 1958). These main factors are integrative, a change in one variable will lead to a change in others resulting in river behavior alterations (D.L., 1994). The primary factors governing in-stream sediment transport are explained in more detail in Section 3.4.

Upland streams are generally characterized by snowmelt runoff and seasonal influxes of cold groundwater, whereas lowland streams are dominated by rainfall hydrology (D.J. & al., 2010), although this will vary with geology and climate. Sediment transport patterns vary both geographically and seasonally (D.J., 2001; Lawler et al., 2003). As sediment travels downstream, the grain size distribution is altered by deposition and transport (K.R., 1995). A steeper slope will reduce the sediment particle's critical shear stress initiating transport sooner than a grade with less incline. Upland rivers typically in steep terrain are composed of gravel-beds (Suttle, 2004) and will deliver more and larger sediment, while lowland slopes tend to be depositional zones (Aksoy, 2005). When fine sediment enters the river it will move through upland drainage networks and eventually discharge into floodplains and the sea (Suttle, 2004).

Seasonal changes also alter sediment erosion, transport and deposition. Seasons of high rainfall and spring melt have the potential to deliver more sediment than events with less rainfall or spring melt (K.R., 1995). The boundaries of a river will change over time based on adjustments to driving variables such of flow patterns (D.L., 1994). For example, seasons of high precipitation will yield higher flows accelerating riverbank instability/erosion which increases the river's width, decreasing sinuosity (meander), increasing slope and sediment transport (D.L., 1994). Sediment movement occurs primarily near the riverbed, usually 0.1-0.2 times the flow depth (Hu et al., 2011). This region constitutes bed-load movement; however, particles here also undergo suspension.

Fundamentally, there are three modes of sediment transport: suspension, traction, and saltation. Suspension is the process by which a sediment particle floats within the moving fluid by stream turbulence, and is typically characteristic of fine particles (silt and clay) with a diameter less than 0.04 mm (Ackers et al., 1973). This mode of transport is classified as suspended load. Traction is the transportation of a particle by rolling and sliding along the bed, usually represented by gravel and cobbles (diameter > 2.5 mm). The third mode of transport, saltation, is characterized by a ballistic trajectory whereby a particle abruptly leaves the bed, is carried in suspension, and then is pulled down by gravity to the riverbed. Frequently this random movement applies to sand particles (Church, 2006; Murphy, 1985), with a diameter greater than 0.04 mm and less than 2.5 mm (Ackers & W.R., 1973). Sediment transport by traction and saltation are customarily classified as bed-load (Church, 2006; Murphy, 1985; Prothero & Schwab, 1996). It is important to note that the same particle transported as bed-load at one time, may jump into suspension at another time or location (Yang, 1996), making it difficult to separate saltating bed-load from intermittent suspension (Church, 2006; Hu & Guo, 2011). A particle's random, bouncing path of travel downstream can eject or strike other sediment causing them to jump and skip into other particles, which propagates the transport process (Prothero & Schwab, 1996). Due to a sediment exchange with bed load, these particles moving by saltation are not considered suspended load (Hu & Guo, 2011).

Based on the source of transported material, total sediment load can be defined as the sum of bed-load and wash load (Yang, 1996). Wash load consists of fine material and depends mostly on watershed runoff, not on the river hydraulics (Yang, 1996), and is therefore considered negligible in this study.

1.4 Global Climate Change and Instream Sediment Transport

Many factors that govern sediment transport react directly to climate change. The Earth's surface temperature is increasing at a rate of 0.17 °C every 10 years (Barnston, 2014; Chaplot, 2007) and water temperature is in close harmony with air temperature (D.J. & al., 2010; Whitehead, 2009). Climate change will likely alter precipitation and air temperature directly affecting the watershed and hydrologic processes including land surface runoff and in-stream flow (Bosch, 2014; Brekke, 2009; Heglund, 2010). Likewise, vegetation and soils will influence climate by releasing and/or absorbing water which have direct feedbacks to temperature, precipitation, and weather patterns (NRC, 1999; T.L., 1988). The interactions between rainfall, temperature, hydrology, and soil resources lead to high variability in future watershed responses (Chaplot, 2007). As weather warms, water temperature is expected to rise, which can change river morphology and water quality (Ficklin et al., 2013; Heglund, 2010). Similarly, warmer temperatures will alter important hydrologic components such as vegetation growth and uptake, evapotranspiration, and soil moisture (Bosch, 2014), making alterations in water resources a critical response to climate change (Hammond, 2007). Other hydrological components, such as precipitation, snowmelt, and groundwater, will also influence stream temperature (Ficklin et al., 2014). In fact, warmer temperatures for locations where snow cover is prominent could cause a shift from less erosive snowfall to more erosive rainfall, enhancing sediment erosion, and consequently altering the sediment load in rivers and biological processes (Ficklin et al., 2013; Nearing, 2004; Wenger et al., 2011).

Global climate change is likely to affect surface runoff by changing erosion patterns, thereby altering soil resources at both watershed and habitat scales (Chaplot, 2007). Extreme rainfall events will alter river velocity (Whitehead, 2009) causing a change in sediment behavior. These results could have growing and irreversible impacts as population continues to grow and alter land cover (Whitehead, 2009). Using a century worth of global data, researchers have also demonstrated a relationship between air temperature and surface runoff. As worldwide air temperature rose by 1˚C, global runoff increased by 4% (Labat, 2004) with North America most sensitive to the recent climatic variations (Prudhomme, 2003). Current research on four Lake Erie watersheds show that climate change will affect land surface runoff, which in turn may increase sediment loads in waterbodies (Bosch, 2014; Chaplot, 2007; Daloglu et al., 2012).

1.5 A small piece of a complex system

Both water temperature and sediment, although small pieces of a complex system, play a key role in ecosystem health and suitability of water resources for human use (Ficklin et al., 2013; Stewart, 2014). The concept of ecosystem health adopted here is defined by Meyer (1997) as "sustainable and resilient, maintaining its ecological structure and function over time while continuing to meet societal needs and expectations." Although much progress investigating the sediment flow process has been made, the effect of water temperature on sediment transport is unclear and often times contradictory (Akalin, 2006; Hong, 1984). Many of the variables and parameters that govern transport and deposition characteristics of sediment are in need of research (Chaplot, 2007). Although depth of flow and water temperature are considered secondary factors, their effects on sediment discharge have not been determined (Colby, 1964). In fact, recent studies looking at the effects of water temperature fluctuations on sediment movement are scarce within the literature (Ficklin et al., 2013). Depending on the rivers' sediment behavior, this information could be a means of linking small-scale understanding to large-scale watershed processes (NRC, 1999). To this end, the contribution of this study is to document the effect of water temperature on instream sediment transport rate.

CHAPTER 2. WHO IS LOOKING AT TEMPERATURE

Changes in climate patterns have the potential to alter evaporation and precipitation, which in turn can lead to acceleration of the hydrologic cycle (Del Genio, 1991; Huntington, 2006; N., 2001). As a result, more surface runoff and sediment could enter rivers and streams. The National Oceanic and Atmospheric Administration (NOAA) published a map showing long-term air temperature trends from data collected over a 64-year period, for January through March season (Figure1). Orange represents an average increase of 0.5°F per decade. The two shades of red show an average increase starting at 1°F and rising greater than 1.2°F per decade. The map illustrates that more than 75% of the lower 48 states has already experienced a rise in air temperatures.

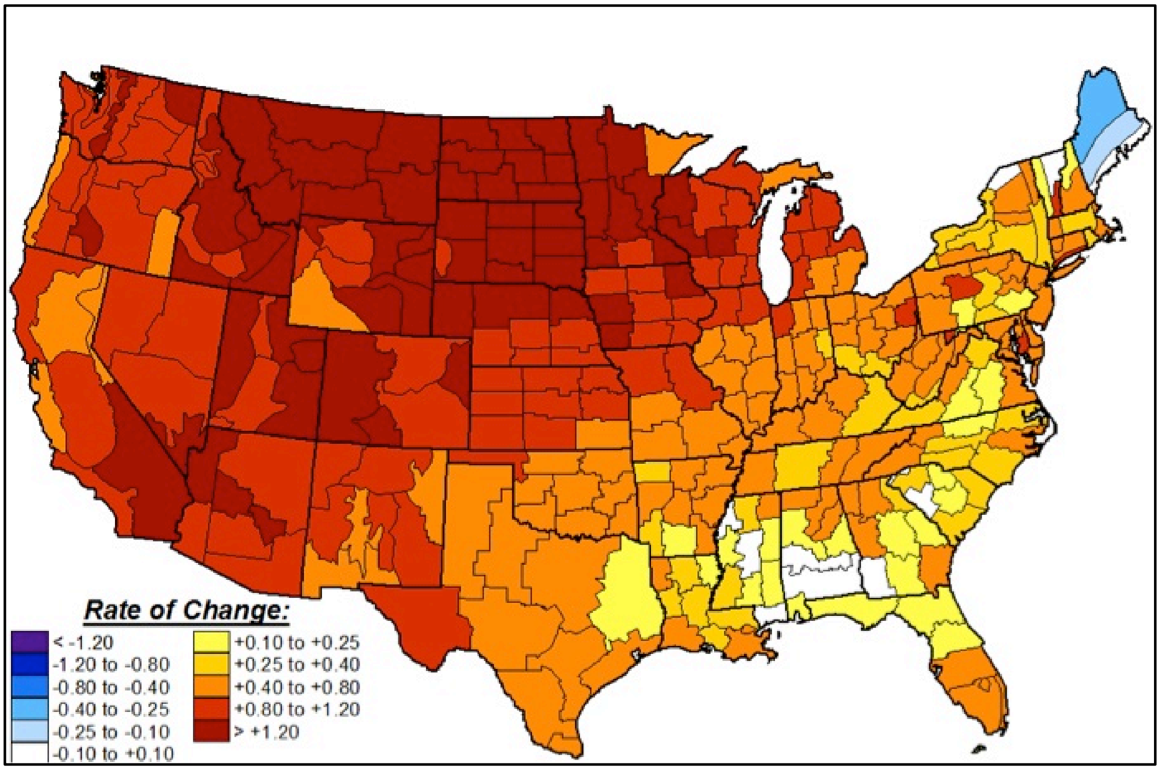

Figure 1. Air temperature trend for the January-March season (degrees F per decade). Image Credit: NOAA Climate Prediction Center. Figure created by employee of the federal government and is in the public domain. See Appendix, pg. 33, for documentation that this material is in the public domain (Barnston, 2014).

In 2014, the Environmental Protection Agency (EPA) released a vulnerability assessment table for region 5, which includes the Great Lakes and the upper mid-west states including Michigan. One of the most emphasized and 'very likely' impacts of climate change is warmer water temperatures. "The likelihood of outcome terminology comes from the Intergovernmental Panel on Climate Change (IPCC), where 'very likely' means 90-100% probability" (EPA, 2014). Risks identified by the EPA because of increased water temperatures include water quality, ecosystem well-being, and wetland health. The assessment highlighted, “the impacts of climate change on the nature of aquatic species in cold-water lakes will tremendously affect habitat ranges, migration patterns and restoration efforts (EPA, (2014).” This likely shift in water temperatures, which may compromise aquatic habitat, also threatens tribal communities that depend on healthy aquatic life for subsistence. The EPA’s report emphasized the urgency and importance of adaptation efforts between states, tribes and Canada.

According to a scientific investigation published for the U.S. Geological Survey and the Department of the Interior, stream segments in Wisconsin are predicted to become 1° to 5°C warmer (Stewart, 2014). Based on summertime stream data collected from 1990-2008 researchers developed a model to predict water temperature under current and future climate conditions. In addition to considering watershed characteristics, the climate inputs include changes in air temperature, soil moisture, and changes in precipitation altering groundwater recharge. This scientific investigation evaluated stream temperature response to climate change for 94,341 kilometers of streams across Wisconsin. The results of this study verified that changes in climate will affect stream temperatures and fish distribution (Stewart, 2014). Researchers have also studied the Columbia River Basin (Ficklin et al., 2014). Using USGS field data and SWAT, they have developed a model for predicting stream temperatures. Results indicate average water temperatures are expected to increase from 1.6° to 5.2° C.

Studies also suggest that snowmelt is a driver of water temperature fluctuations in rivers and streams. Point Blue, a conservation science and research group studies Arctic Sea ice volume. Data was collected from 1979 to 2013 and studies indicate roughly a 60% melt over the past 34 years (Cohen, 2014). Although the fact that snowmelt influences water temperature is well known, the tendency for it to buffer stream temperatures against increases in air temperature depends on the region (Ficklin et al., 2014).

2.1 Research on Water Temperature and Sediment Transport

Research on water temperature effects on sediment transport started in the late 1930’s; however, at the time, both lab and field investigations often reported conflicting results (Akalin, 2006; Hong, 1984). For instance, Ho (1939) determined that at colder water temperatures more bed particles were transported, whereas Mostafa (1949), reported that warmer water temperatures carry more bed sediment than colder temperatures.

A field study conducted by Lang et al. (1949) measured the sediment load in the Colorado River at two locations, both upstream from dams. They reported that average sediment loads decreased significantly in summer (at 29.44 °C), compared to the sediment loads in the winter (at 10 °C). In other words, a decrease in water temperature by 19.44 °C, caused the sediment load to increase more than twice. Similar results were reported in a laboratory experiment performed by Straub et al. (1958) in a re-circulating flume. Under a constant water discharge, the sediment load tripled over a water temperature decrease of 28 °C. However, contradicting results were reported by Toffaleti (1968), who studied the effect of increasing water temperatures on sediment loads in large rivers. He documented a rapid increase in sediment transport with water temperatures warming to 26 °C and then only a slight decrease in sediment movement as water temperatures continued to warm.

In more recent laboratory work, Hong et al. (1984) studied sediment concentrations at different flow conditions with water temperatures between 0° and 30° C. Results showed that as water temperature increased from 1° to 30° C, flowing at a velocity of 1.38 ft/s, the bed-load sediment decreased from 1537 ppm to 203 ppm. Additionally, over the same temperature range, flowing at 2.23 ft/s, the bed-load sediment dropped from 1060 ppm to 109 ppm. Comparing these two cases with a change in velocity, and all other variables remaining constant, the faster flow yields a greater decrease in sediment concentration, by over two times as much, for a temperature range from 1° to 30° C. The research team concluded that the lower viscosities associated with warmer water temperatures increase the sediment particle fall velocity, resulting in lower sediment concentration.

Colby (1964) documented results from a laboratory experiment using 0.4mm sand and three different water temperatures at a fixed velocity and depth. His results show the bed-load discharge increased by 18.5% for a temperature change from 26.7 to 15.6°C. At colder temperatures, from 15.6 to 4.4°C, the bed-load discharge increased by 34.4%. Colby argued that the effect of the temperature on fall velocity was relatively small in shallow flumes and comparatively large for deep natural rivers, depending on the particle size. Table 1 summarizes these research findings.

Table 1. Past research documenting the effect of water temperature on sediment outcomes. The top two studies report similar findings, yet different venues. The bottom three studies report conflicting results.

Date	Who	Venue	Results
1949	Lang et al.	Field	As Water Temp Cools (19°C temp change) Average Sediment Conc., Increase 2.5x
1958	Straub et al.	Lab Flume	As Water Temp Cools (28°C temp change) Total Sediment Conc., Increase 3x
1968	Toffaleti	Field	As Water Temp Warms to 26°C Bed-load Transport Rate, Rapid Increase
1984	Hong et al.	Lab Flume	As Water Temp Warms, 1 to 30°C Bed-load Sediment Conc., Decreased 10x
1964	Colby	Lab Flume	As Water Temp Warms, 4.4 to 26.7 °C Bed-load Transport Rate, Decreased < 2x

In spite of this research, the effects of water temperature fluctuations on sediment transport remain unclear. Furthermore, as indicated from the past studies, results are conflicting and vary widely. Therefore, in light of global climate change, a better understanding of the sediment responses to changes in water temperature is needed (Chaplot, 2007).

The purpose of this study is to document the effect of water temperature on sediment concentration (ppm) and sediment transport rate (kg/s). Two model equations are provided as tools to estimate sediment transport as a function of water temperature, for rivers with characteristics similar to the Niobrara River (see Table 2). Additionally, this analysis provides a useful procedure that decision makers could use to predict in-stream sediment yields as a function of changing water temperature.

CHAPTER 3. SEDIMENT TRANSPORT MODELS

Six easily implemented and common sediment transport models are examined here. A brief explanation for each of the six sediment transport methods and the corresponding equations are described below. The water temperature-dependent variables are highlighted and boxed in red color for easy recognition. A tabular format showing all methods and their corresponding experimental variables are shown in Table 4.

3.1 Bagnold's Approach

Bagnold (1966) was one of the earliest researchers to use the stream power concept to develop a sediment transport model. His relationship considered the rate of work done by the stream and the energy available in moving the sediment. Bagnold's method was based on laboratory data and he developed a graphical relationship using bed shear stress and sediment size. The sediment mobility is expressed as:

$$q_t = q_{bw} + q_{sw} = \frac{\gamma}{\gamma_s - \gamma}\,\tau V\left(\frac{e_b}{\tan\alpha} + 0.01\frac{V}{\omega}\right)$$

Where, q_t = total transport rate by weight, (lb/s)/ft. channel width

q_{bw} = bed-load transport rate by weight per unit channel width,

q_{sw} = suspended load discharge in dry weight per unit time and width,

γ_s and γ=specific weights of sediment and water, respectively,

τ = shear force acting along the bed,

V = average flow velocity,

e_b = efficiency coefficient of bed-load (function of V and sediment size)

ω = fall velocity of suspended sediment, and

tan α = ratio of tangential to normal shear force.

3.2 Ackers and White's Approach

Ackers and White (1973) expanded on Bagnold's stream power theory and developed several generalized dimensionless sediment transport parameters, based on sediment size greater than 0.04 mm and a Froude number less than 0.8. Using laboratory data and optimizing a best-fit curve, they established relationships between the sediment size (d_{gr}), the initial motion parameter (A), and the transition zone parameter (n). They hypothesized the effectiveness of the channel boundary shear stress on sediment movement depends on whether the particles are coarse or fine. In the case of fine sediment, total shear stress is effective in transporting sediment, whereas with coarse sediment, only part of the shear stress on the channel bed causes sediment movement (Yang, 1996). Ackers and White's approach is expressed as follows:

$$F_{gr} = U_*^n$$

$$\left[gd\left(\frac{\gamma_s}{\gamma} - 1\right)\right]^{-1/2}\left[\frac{V}{\sqrt{32}log(^{\alpha D}/_{d})}\right]^{1-n}$$

$$d_{gr} = d\left[\frac{g(^{\gamma_s}/_{\gamma} - 1}{v^2}\right]^{1/3}$$

Where F_{gr} = total sediment concentration by weight, ppm,
U_*= shear velocity,
n = transition exponent, sediment size dependent,
α = coefficient in rough turbulent equation (=10),
d = sediment particle size,
D = water depth,
d_{gr} = dimensionless grain diameter, and
v = kinematic viscosity.

3.3 Yang's Approach

Yang (1972) questioned whether conventional sediment transport parameters such as flow, velocity, energy slope and shear stress are effective for calculating sediment mobility. He reviewed basic equation assumptions and determined that the rate of energy per unit weight of water in moving sediment must be directly related to the rate of energy available to a unit weight of water. In other words, total sediment concentration must be directly related to unit stream power. In an open channel with a length x and total slope Y, Yang's equation for unit stream power, VS, is the product of velocity and channel slope, expressed as:

$$\frac{dY}{dt} = \frac{dx}{dt}\frac{dY}{dx} = VS$$

Where V = velocity (length, x / time, t), and
S = slope.

After running multiple regression analysis for 1093 sets of laboratory data and 166 sets of river data, Yang (1979) developed a relationship between sediment concentration and unit stream power as expressed in the following equation:

$$logC_{ts} = 5.435 - 0.286\log\left(\frac{\omega d}{v}\right) - 0457\log\left(\frac{U_*}{\omega}\right) + \left(1.799 - 0.409\,log\left(\frac{\omega d}{v}\right) - 0.314\log\left(\frac{U_*}{\omega}\right)\right)\log\left(\frac{VS}{\omega} - \frac{V_{cr}S}{\omega}\right)$$

Where C_{ts} = total sand concentration by weight, ppm,
U_*= shear velocity= $(gDS)^{1/2}$,
VS = unit stream power,
v = kinematic viscosity,
ω = fall velocity of sediment, and
d = median particle diameter.

The application of Yang's approach is limited to the sand-size particle range. It is important to note here the difference in Bagnold's (1966) and Yang's (1973, 1979) approach. Both theories look at the stream energy concept. Bagnold emphasizes that stream energy applies to the power per unit area acting along the bed (based on general physics, the rate of work being done should be related to the power available times the efficiency of the system). In contrast, Yang highlights the stream power available per unit weight of fluid to move sediment. As a result, Yang considered relationships between relevant sediment mobility variables.

3.4 Laursen's Approach

Based on laboratory flume data, Laursen (1958) established a functional relationship between sediment concentration and flow parameters, such as velocity, bed-load, and suspended load, for a median particle size between 0.088 and 4.08mm. According to Yang (1996) the method was favorable, and in 1971, an ASCE task committee expressed Laursen's formula in a dimensionally homogeneous form as:

$$C_t = 0.01\gamma \sum_i p_i \left(\frac{d_i}{D}\right)^{\frac{7}{6}} \left(\frac{\tau'}{\tau_{ci}} - 1\right) f\left(\frac{U_*}{\omega_i}\right)$$

Where C_t = total average sediment concentration, ppm,
U_*= shear velocity= $(gDS)^{1/2}$,
p_i = percentage of material available in size fraction i,
ω_i = fall velocity of particles of mean size d_i,
τ' = Laursen's bed shear stress for d_{50}, and
τ_{ci} = critical tractive force for sediment size d_i as given by the Shields diagram.

3.5 Shen and Hung's Approach

Shen and Hung (1972) developed a regression equation based on 587 sets of laboratory data in the sand-size sediment range. Taking their data analysis a step further, they performed a sensitivity analysis on the importance of different variables to the transport rate of sediment. Their analysis indicates that the rate of sediment motion is not sensitive to changes in water depth. Their regression equation is:

$$log\ C_t = \begin{array}{c} 107\,404.459\,381\,64 + 324\,214.747\,340\,85Y \\ -326\,309.589\,087\,39Y^2 + 109\,503.872\,325\,39Y^3 \end{array}$$

Where, C_t = total sediment concentration by weight, ppm,

$Y = (VS^{0.57}/\omega^{0.32})^{0.007\,501\,89}$,

VS = unit stream power, and

ω = average fall velocity of sediment particles

3.6 Colby's Approach

Colby's (1964) sediment transport research stemmed from both laboratory and field data. He used Einstein's (1950) bed-load function as a framework to develop three graphical relationships for total load. The first graph is used to determine uncorrected sediment discharge (q_{ti}), using a given velocity, water depth, and median sediment size. The second graph shows the relationship between the water temperature and concentration of fine sediment to the discharge of sands to mean velocity, providing values for $k_1$and k_2. The third graph gives k_3, based on median size of sediment. Colby's method is limited to rivers with a median sediment diameter less than 0.6 mm and water depths less than 3 meters.

$$q_t = [1 + (k_1 k_2 - 1)0.01k_3]q_{ti}$$

Where q_t = total sediment discharge, (ton/day)/ft. of channel width,

k_1 = correction factor for water temperature,

k_2 = correction factor for effect of concentration of fine sediment,

k_3 = correction factor for median particle size, and

q_{ti} = uncorrected sediment discharge.

CHAPTER 4. DEMONSTRATION PROCEDURE

Six common sediment transport methods were employed to document sediment behavior over nine water temperatures ranging from 1-40 ˚C, in 5 ˚C increments. The methods were selected because they are common and simple total-load sediment yield equations. The sediment transport methods used in this study are: Bagnold's Method (1966), Ackers and White's Method (1973), Yang's Method (1972), Laursen's Method (1958), Colby's Method (1964), and Shen and Hung's Method (1972). Each of these methods are described in Chapter 3.

4.1 Sample Application

The six sediment transport models were employed on a site in the well-studied Niobrara River to demonstrate a procedure that will estimate the potential instream sediment yield as a function of water temperature. The river characteristics were obtained from USGS gaging station #06461500 near Sparks, Nebraska. The river characteristics are held constant in all calculations and are shown in Table 2. River variables that affect sediment transport will be explained further in Section 4.2.

Table 2. Niobrara River characteristics under steady flow conditions at one particular location/cross section. Variables are held constant in all calculations.

Median Particle Size	0.283mm	0.011 inches
Velocity	112.8 cm/s	3.7 ft/s
Slope	0.00169	0.00169
Channel Width	21.64 m	71 ft
Average Depth	52.73 cm	1.73 ft
Channel Length	804.7 km	500 miles
Drainage Area	18,130 km^2	7000 $miles^2$

Two USGS gaging stations document temperature data for the Niobrara River. Gaging station number 06461500 near Sparks, Nebraska collected a water temperature range from 0 to 31.5 ˚C, from March 26, 2014 to November 16, 2014. The coldest water temperatures reported were 0.6 ˚C in April and 0.0 ˚C in November, with the warmest temperature at 31.5 ˚C in July. To the southeast, 127.7 miles downstream, gaging station number 06465500 near Verdel, Nebraska collected water temperatures ranging from 0.3 to 34.9 ˚C from October 11, 2010 to June 15, 2015. The coldest water temperature reported was 0.3˚C starting in November and holding steady through mid-March. The warmest temperatures were collected in July at 34.7 ˚C. Table 3 summarizes the findings from these two gaging stations. This study, therefore, considered temperature ranging from 1 to 40 ˚C.

Table 3. Niobrara River gaging stations, range of water temperature and collection dates.

Gaging Station	Nebraska Location	Collection Dates	Coldest and Warmest Water Temp. °C
#06461500	near Sparks	March, 26 2014 to Nov.,16-2014	0.0 (Nov) to 31.5 (July)
#06465500	near Verdel	Oct.,11, 2010 to June 15, 2015	0.3 (Nov) to 34.9 (July)

Table 4 summarizes the experimental parameters used in developing the six sediment transport methods. Ranges for particle size, velocity, water depth, slope, width, water temperature, and the experimental venue are shown. The Niobrara River characteristics are also shown in the bottom row as a case study comparison. The grayed-in boxes highlight the parameters found in both the sediment transport models and the Niobrara River. The red arrows point to the two sediment transport models (Yang and Colby) whose experimental conditions encompass the range of conditions in the Niobrara River. These two methods were analyzed using both laboratory flume and field data. Shen and Hung's method tested in a laboratory flume matches all river parameters except channel width. Ackers and White's method also tested in the lab includes all but two Niobrara parameters, depth and width. Bagnold's method matches only Niobrara's particle size, and Laursen's method matches only the slope, both of which are laboratory experiments.

Table 4. Six sediment transport methods and the experimental parameters under which the methods were developed. The Niobrara River characteristics are listed in the bottom row. The gray boxes represent parameters found in both the Niobrara River and the sediment transport method. Yang and Colby Methods (highlighted with a red arrow) incorporate all Niobrara River characteristics.

Methods	**Parameters**						
	Particle Size (mm)	Velocity (cm/s)	Water Depth (cm)	Longitudinal Slope	Channel Width (m)	Water Temp (◦C)	Venue
Bagnold	0.18-0.79	1.1-4.0	4.9-42.7	-	0.3-2.4	-	Lab
Ackers & White	0.04 - 7.0	2.1-216.4	0.30-42.7	0.00006-0.037	0.07-1.22	7.8 - 31.7	Lab
Yang	0.15-1.7	24.4-195.1	1.2-1,524	0.000043-0.028	0.13-533.4	0 - 34.4	Lab & Field
Laursen	0.1	32.6-102.4	7.62-30.3	0.0004-0.0018	0.91	-	Lab
Shen & Hung	0.13-1.3	21.3-198	2.1-85.3	0.00015-0.027	0.27-2.4	0 – 38	Lab
Colby	0.18-0.70	21.3-243.8	6.1–1737.4	0.000031-0.010	0.27-914.4	0.27-914.4	Lab & Field
Niobrara River	0.28	112.8	52.73	0.00169	21.64	14.4	Field

4.2 Sediment Transport Variables

The main variables used in the sediment transport calculations are specific weight of sediment (γ_s), specific weight of water (γ), flow velocity (V), kinematic viscosity of water (v), and sediment particle fall velocity (ω). The temperature dependent variables are kinematic viscosity of water (v), specific weight of water (γ), and the sediment particle fall velocity (ω).

4.2.1 Water Properties

The specific weight of water (γ) over the temperature range from 1 to 40 ˚C changed by 0.77%. Due to this small change, the specific weight of water (γ) was held constant at 9806 N/m^3 (62.38 lb/ft^3) for all calculations. The values of kinematic viscosity and fall velocity changed considerably in response to a change in water temperature (see Figures 2 and 3). These two water properties are explained in more depth below.

4.2.2 Effect of water temperature on kinematic viscosity, ν

Fundamentally, water viscosity results from the interaction and cohesion between water molecules. The higher the viscosity, the more resistance or opposition to flow. Kinematic viscosity (ν) is defined as the ratio of dynamic viscosity (μ) and density (ρ) and is expressed as $\nu = \mu/\rho$. Water temperature has a significant effect on the kinematic viscosity. As water temperature warms from 1 to 40 °C, viscosity decreases by 171% (Figure 2). The corresponding tabular results are located in the Appendix, Table A.1. The relationship between water temperature and kinematic viscosity were obtained from the International Association for Properties on Water and Streams (IAPWS, 2011).

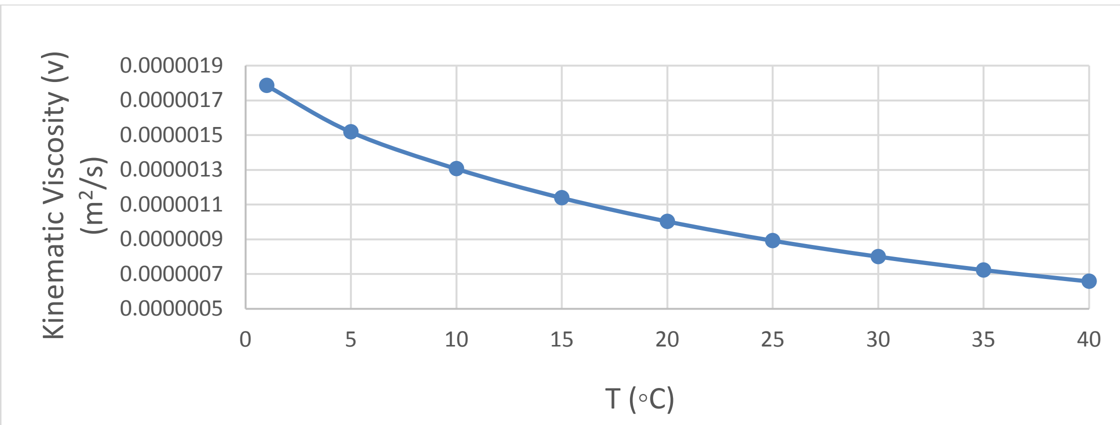

Figure 2. Relationship of kinematic viscosity to water temperature. Kinematic viscosity was obtained from the International Association for Properties on Water and Streams (IAPWS, 2011).

4.2.3 Effect of water temperature on sediment particle fall velocity (ω)

According to Yang (1996), "fall velocity is the average terminal settling velocity of a particle falling alone in quiescent distilled water of infinite extent." This fall velocity (ω) is directly related to relative flow conditions between the sediment particle and water during conditions of sediment entrainment, transportation, and deposition. The fall velocity (ω) is a function of sediment size (d_{50}), kinematic viscosity of water (ν), and the specific weights of sediment (γ_s) and water (γ). Sediment particle fall velocity (ω) is expressed as:

$$\omega = F\left[dg\left(\frac{\gamma_s - \gamma}{\gamma}\right)\right]^{1/2}$$

Where, F is the settling coefficient dependent on sediment size and water temperature expressed as:

$$\left[\frac{2}{3} + \frac{36v^2}{gd^3\left({\gamma_s}/{\gamma-1}\right)}\right]^{1/2} - \left[\frac{36v^2}{gd^3\left({\gamma_s}/{\gamma-1}\right)}\right]^{1/2}$$

d = median particle size (d_{50})
g = gravitational acceleration
γ_s= specific weight of sediment
γ = specific weight of water
v = kinematic viscosity of water

Figure 3 shows the relationship between fall velocity and water temperature. The trend shows a 48% increase in fall velocity over the temperature range from 1 to 40 °C. Simply stated, as the water temperature rises, the fall velocity of the sediment particle increases due to the decrease in fluid viscosity. The values of fall velocity relative to sediment size, water temperature, and shape factor was obtained from the U.S. Inter-Agency Committee on Water Resources (1958). Tabular values that correspond to Figure 3 are provided in Table A.1 in the Appendix.

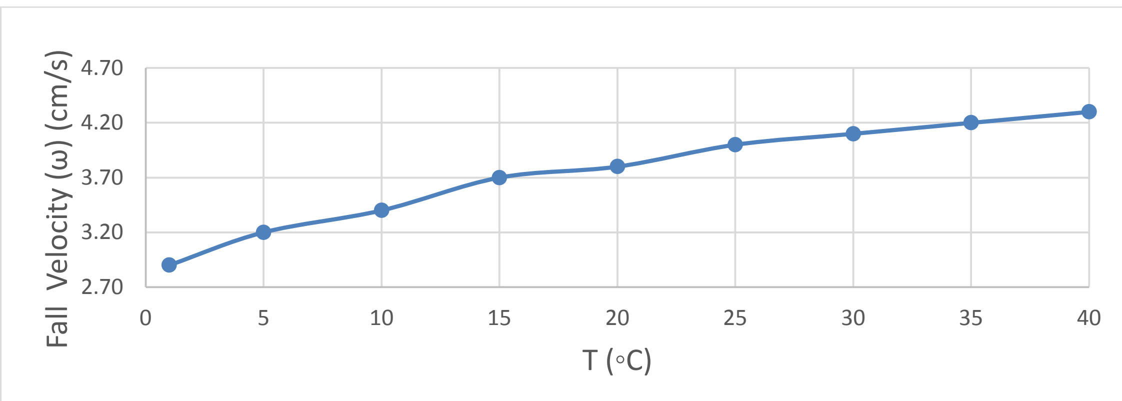

Figure 3. Relationship of fall velocity to water temperature. Fall velocity was obtained from a graph developed by the U.S. Inter-Agency Committee on Water Resources (IACWR, 1958).

4.2.4 Sediment Particle Characteristics

The focus of this study considers sand particles, 0.06mm to 2mm, which are most common in river systems (Church, 2006). For most natural sands, a shape factor of 0.7 should be used (Yang, 1996). Waterborne sediment particles are primarily quartz with a specific gravity of 2.65 (Yang, 1996). Therefore, the specific weight (γ) of sediment was held constant at 2,643 kg/m^3 (165 lb/ft^3). The median particle size (d_{50}) for the Niobrara River is 0.283mm or 0.011 inches (citation), which does fall in the sand range.

4.3 Sediment Transport Calculation Method

Sediment concentrations (ppm) and sediment transport rates (kg/s) were calculated at 5°C water temperature increments ranging from 1 to 40°C. The sediment outcomes for all six methods are documented in Figures 4 and 5. In addition, an average was taken over all the methods, excluding Ackers & White's method (1973), which was considered an outlier. The average was taken in order to establish a simple equation that will provide a quick ballpark estimate for instream sediment potential. Once the average of all the methods was determined, the methods were normalized using the maximum values for sediment concentration, transport rate, and water temperature. In order to establish a curve-fit equation for the average, data points from the normalized average method were put into Table Curve Software (Systat Software Inc., 2015). The equation is known as the "5-model average" and is further described in the Results section. The final analysis considered two of the sediment transport models, Yang and Colby, that incorporated both laboratory and field data to establish their sediment transport equations. Similar to the "5-model average," the two models were averaged, normalized, and a curve-fit equation established for the normalized average data. This equation is referred to as the "2-model average" and further explained in the Results section. Please refer to Table 4 for specific parameters corresponding to each of the five models.

4.4 Model Assumptions

All variables, except water temperature-dependent variables, were held constant. These Niobrara River characteristics are shown in Table 2. The sediment particles are assumed uniform and non-cohesive (a median particle size, $d_{50} > 0.062$ mm (e. a. Lane, 1949)). All methods were calculated under steady flow by gravity. Steady flow implies no temporal change in velocity or water depth. Each sediment transport model was calculated at 5°C increments. Since each of the models tested are a continuous mathematical function, intermediate values of sediment transport will follow the same trend, therefore calculations at smaller intermediate increments are not necessary.

CHAPTER 5. RESULTS

5.1. Effect of Water temperature on Sediment Yields

The results varied widely among models and indicated that sediment outcomes are sensitive to changes in water temperature. Figure 4 shows the relationship between sediment concentrations, C_t (ppm), and water temperature, T (°C). Both sediment concentration and transport rate show the same trend with respect to change in water temperature for all methods except Acker's and White's method. Bagnold's approach reports the lowest sediment concentration and movement over all water temperature ranges, with Laursen following closely behind as the second lowest prediction. Colby's approach yields outcomes relatively insensitive to temperature compared to other methods. At the coldest water temperature, Ackers and White, yields the fourth highest result and continues to increase as the water warms. Yang yields the second highest results at the coldest water temperature, decreasing from 1 to 15 °C and from 20 to 25 °C. However, from 15 to 20 °C and 25 to 40 °C, Yang's approach yields a slight increase in sediment transport. Shen and Hung yields the highest predictions at 1°C and decreases as water warms. Tables A.2 and A.3, in the Appendix, show numerical results that correspond to Figures 4 and 5.

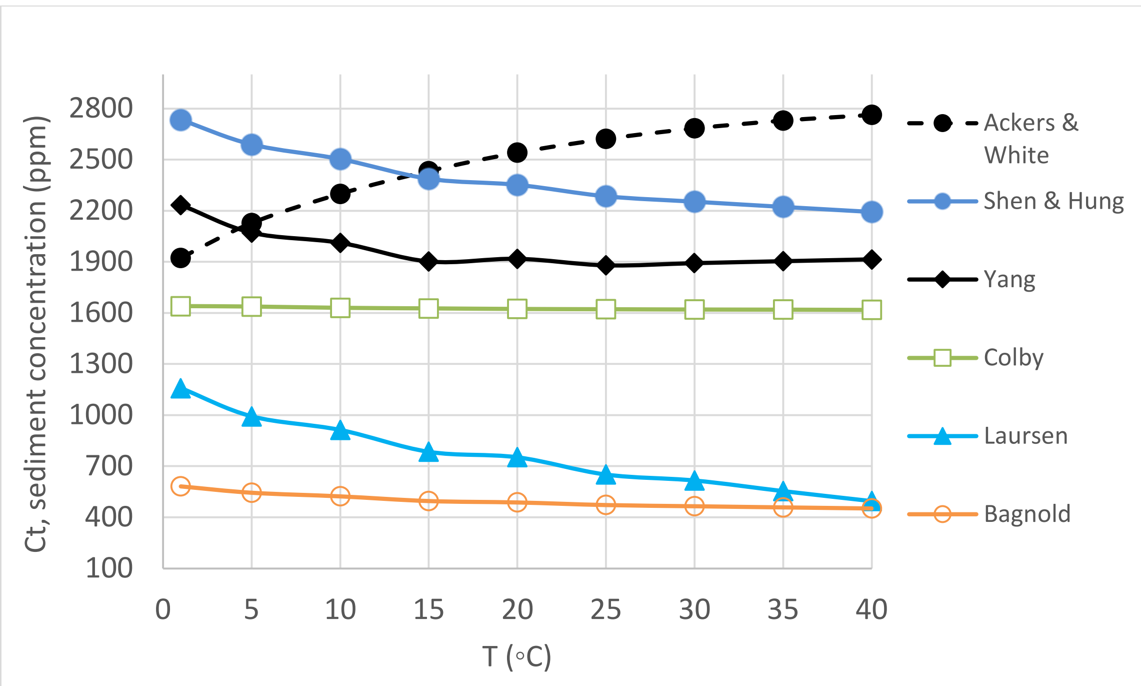

Figure 4. Effect of water temperature on sediment concentration for all methods.

For both sediment concentration and sediment transport rate, four of the six methods show a decreasing trend as water temperatures increase. Yang's method yields a slight increase of less than 1% as water temperatures warm to 40 °C. Ackers and White predict an increase in sediment concentration of 30%, as the water temperature warms from 1-40 °C. Because the value for Ackers and White does not follow the same trend as the other five methods, the results were treated as an outlier and are not included in further analysis. Similarly, Figure 5 illustrates the relationship between sediment transport rate, Q_s (kg/s) and water temperature T (°C).

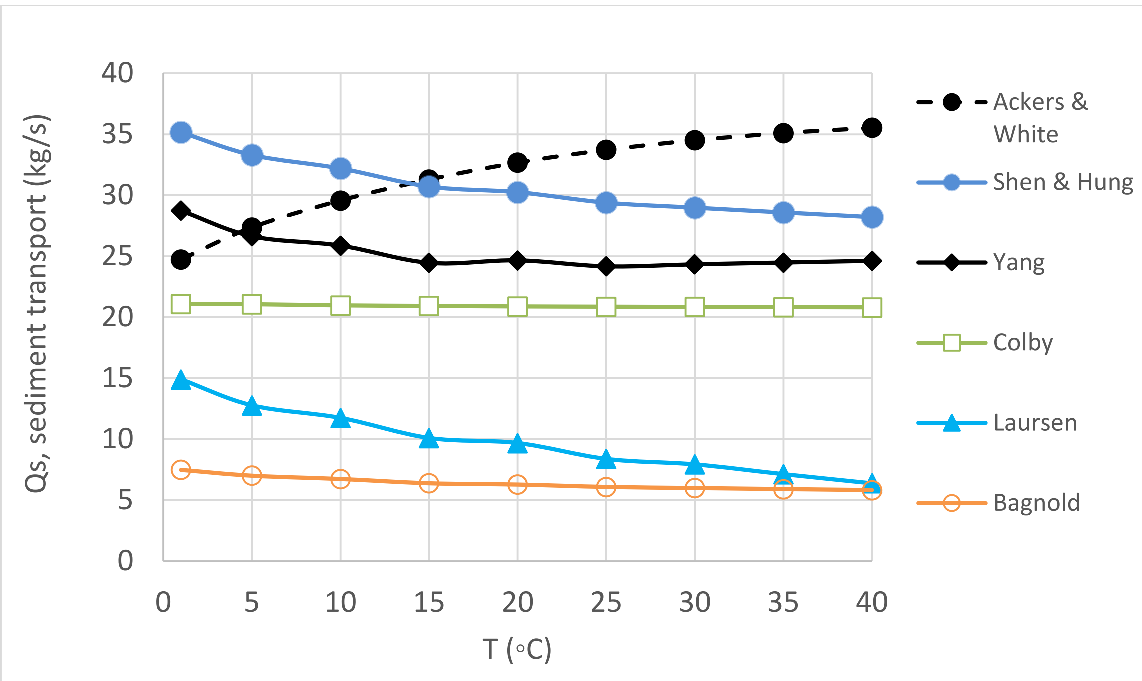

Figure 5. Effect of water temperature on sediment transport rate for all methods.

5.2 Data Analysis for the "5-model average"

Using a simple approach, the average was taken across each 5°C water temperature increment for all methods, excluding Ackers and White's method (which was considered an outlier). The red line in Figures 6 and 7 illustrate the average over all methods.

5.2.1 Uncertainty: 5-model average

Uncertainty for the "5-model average" was calculated. Due to the small sample size of five, high variability is expected (Bilal 2011), therefore a 90% confidence interval was selected for this study. The model average produces a range of error about the mean from 34% to 40% as water temperature warms. For example, at 10 °C the "5-model average" yields 1516 ppm in sediment concentration, with a range at ± 529 ppm. Figures 6 and 7 illustrate the 90% confidence interval and the corresponding tabular values are provided in the Appendix, Tables A.4 and A.5. The equation used to calculate the 90% confidence interval is expressed as:

$$\overline{X} \pm 1.645\sqrt{\frac{S^2}{n}}$$

Where $\overline{X}$= sample mean,

S = standard deviation of the five methods, and

n = number of methods

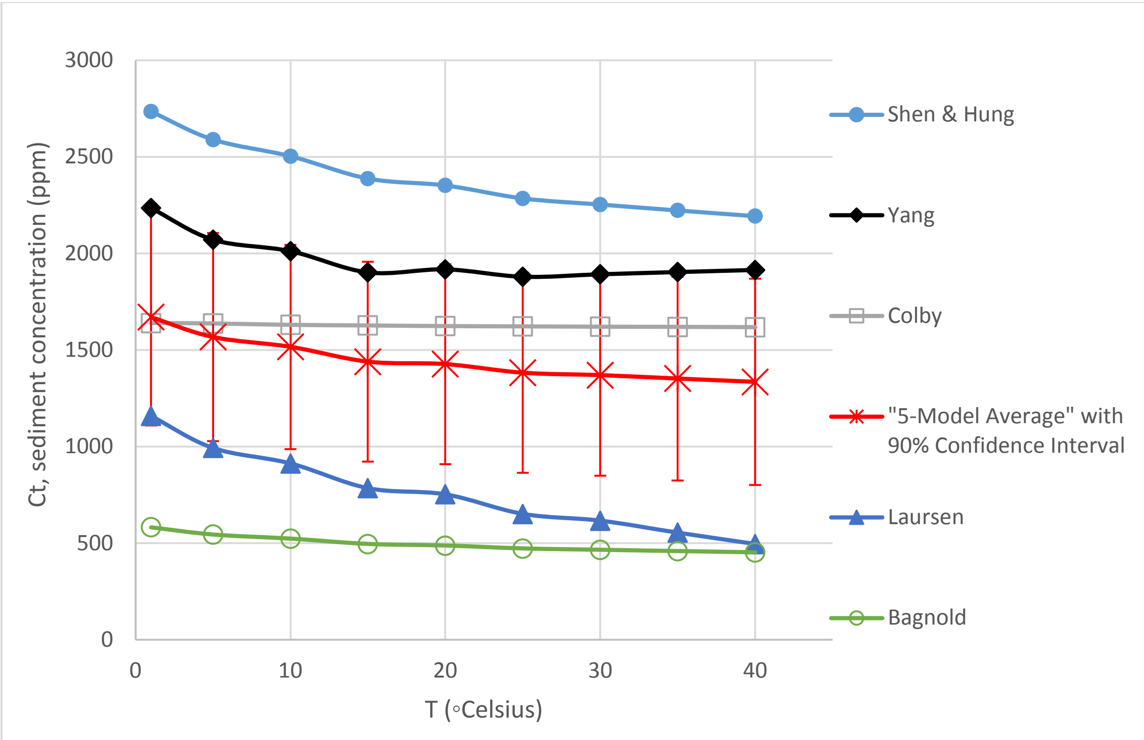

Figure 6. Effect of water temperature on sediment concentration for selected methods, excluding the outlier. The "5-model average" with 90% confidence intervals ranging from 34% to 40% as water temperature warms are shown in red.

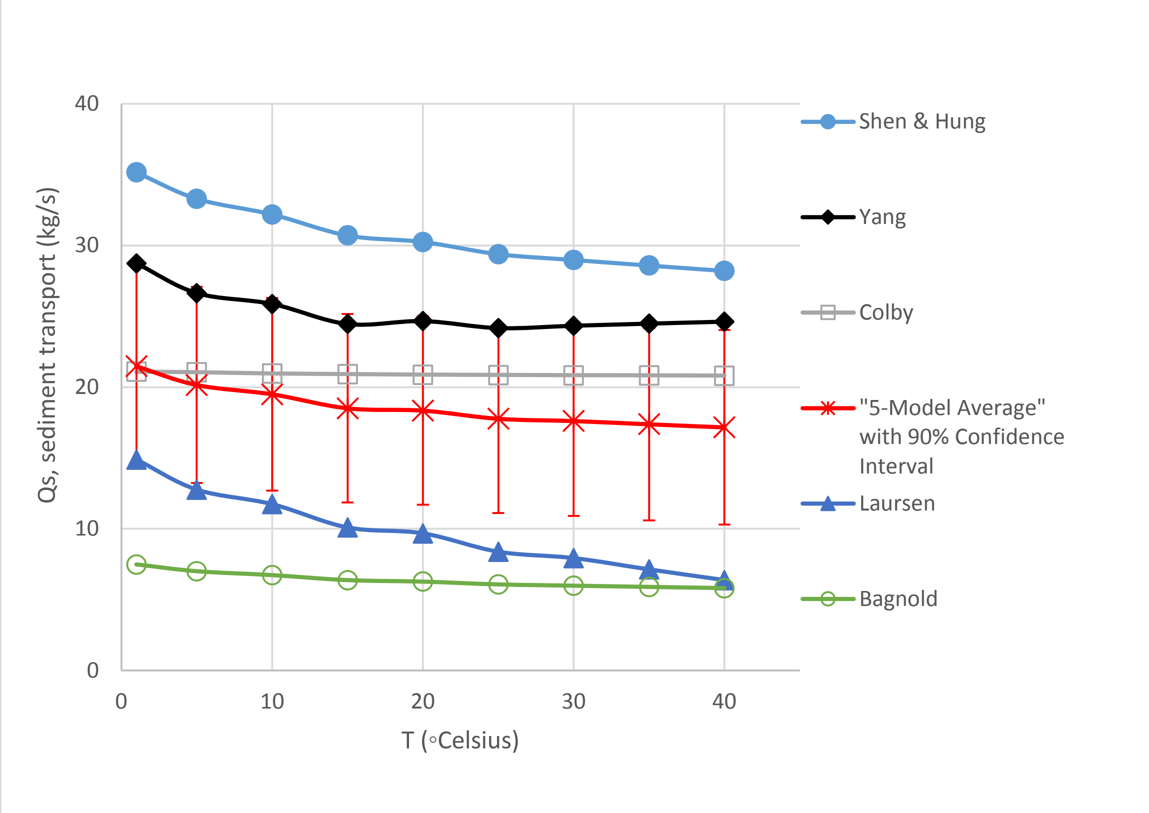

Figure 7. Effect of water temperature on sediment transport rate for selected methods, excluding the outlier. The "5-model average" with 90% confidence intervals ranging from 34% to 40% as water temperature warms are shown in red.

5.2.2 Normalized Values: 5-model average

The values of all sediment outcomes were normalized. To do so, the results of sediment concentration and transport rate for each method were divided by their corresponding maximum sediment value. Likewise, to normalize water temperature, each temperature value was divided by the maximum temperature. The normalized results are shown in Figure 8. The "5-model average" is denoted by the red line. The corresponding tabular values are located in the Appendix, Tables A.5, A.6, and A.7.

5.2.3 Curve Fit Equation: 5-model average

Table Curve 2D software was developed by SYSTAT Software Inc (2015). The software was used to determine a curve-fit equation for the average line of all methods, excluding the outlier. The software output 97 curve-fit equations and ranked them all based on precision. The second ranked equation was selected, based on both simplicity and the correlation coefficient, R^2, value equal to 0.9908. The curve-fit line for this study is denoted as the "5-model average".

The "5-model average" equation is expressed in the following form:

$$C_t/C_{tmax} \ or \ Q_s/Q_{smax} = \frac{1}{(0.955 \ + \ 0.306 \ (T/T_{max})^{0.5} \ )}$$

Where,

C_t = Sediment concentration (ppm) normalized over the maximum sediment concentration, C_{tmax}

Q_s = Sediment transport rate (kg/s) normalized over the maximum sediment transport rate, Q_{smax} and

T = Temperature (◦C) normalized over the maximum temperature, T_{max}.

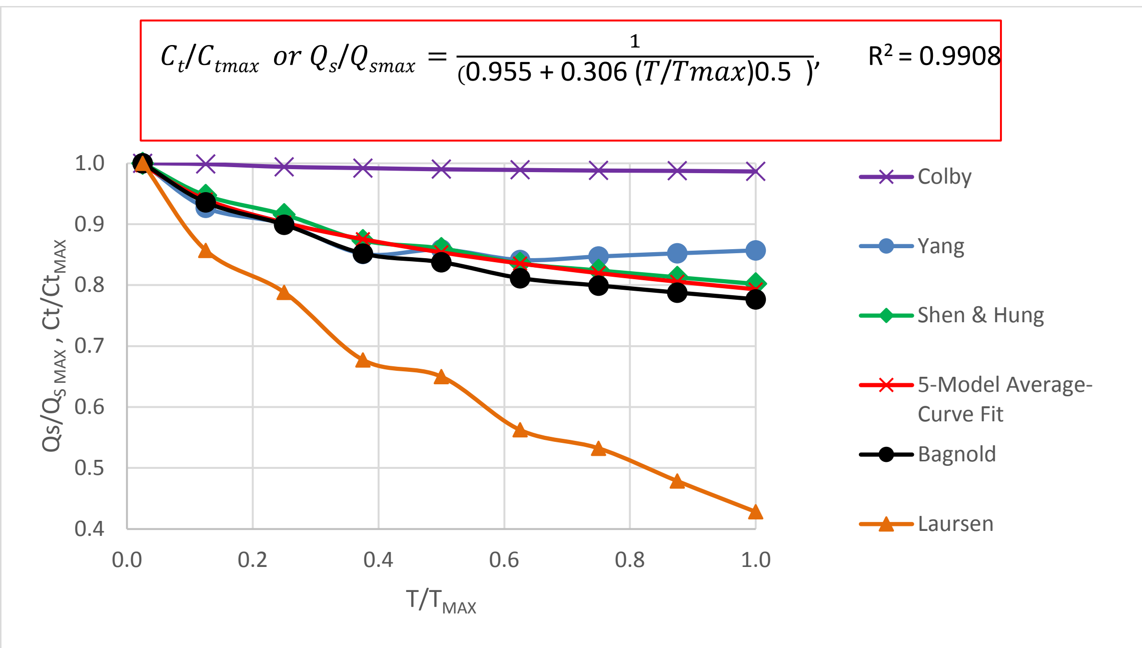

Figure 8. The effect of water temperature on sediment concentration and transport rate for selected methods, including the "5-model average" in red. The "5-model average" curve-fit equation and corresponding R^2 value is boxed in red. All values normalized.

5.3 Data Analysis for the "2-model average"

The Yang and Colby methods encompass Niobrara River characteristics and consist of both laboratory flume and field experiments (documented in Table 4). Plots of Yang and Colby methods with a "2-model average" showing a 90% confidence interval are shown in Figure 9 and 10.

5.3.1 Uncertainty: 2-model average

Uncertainty for the "2-model average" was calculated. Due to the small sample size of two, high variability is expected (Bilal 2011), therefore a 90% confidence interval was selected for this study. The model average produces a range of error about the mean from 18% to 10% as water temperature warms. For example, at 10 °C the "2-model average" yields 1821 ppm in sediment concentration, with a range at ± 222 ppm. Figures 9 and 10 illustrate the 90% confidence interval and the corresponding tabular values are provided in the Appendix, Tables A.4 and A.5. The equation used to calculate the 90% confidence interval is expressed as:

$$\overline{X} \pm 1.645\sqrt{\frac{S^2}{n}}$$

Where $\overline{X}$ = sample mean,

S = standard deviation of the two methods, and

n = number of methods

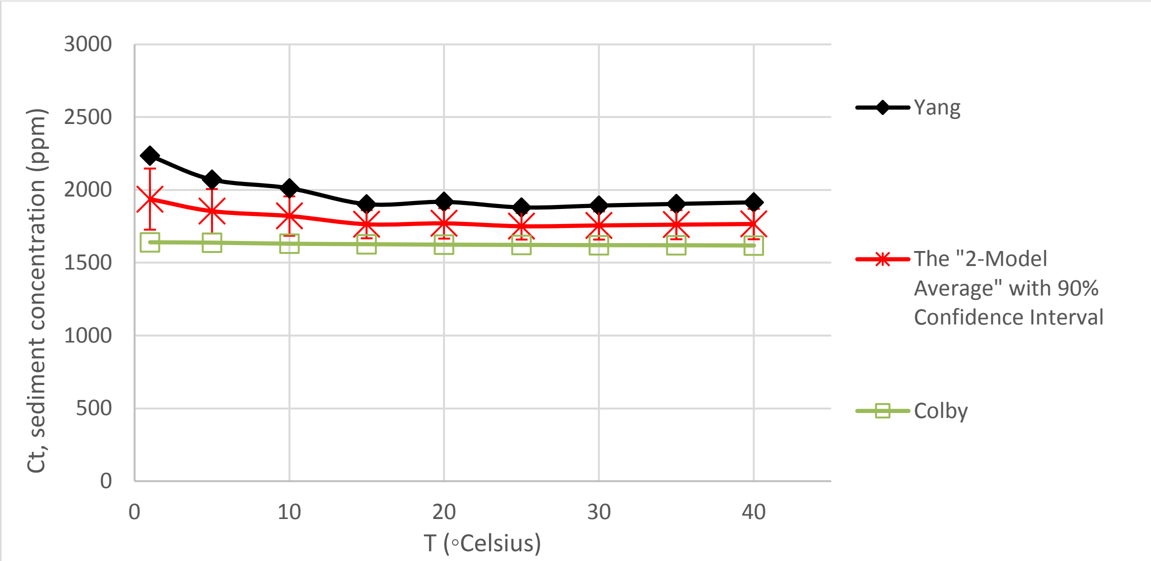

Figure 9. Effect of water temperature on sediment concentration for Yang and Colby methods. The "2-model average" with 90% confidence intervals ranging from 18% to 9% as temperature warms are shown in red.

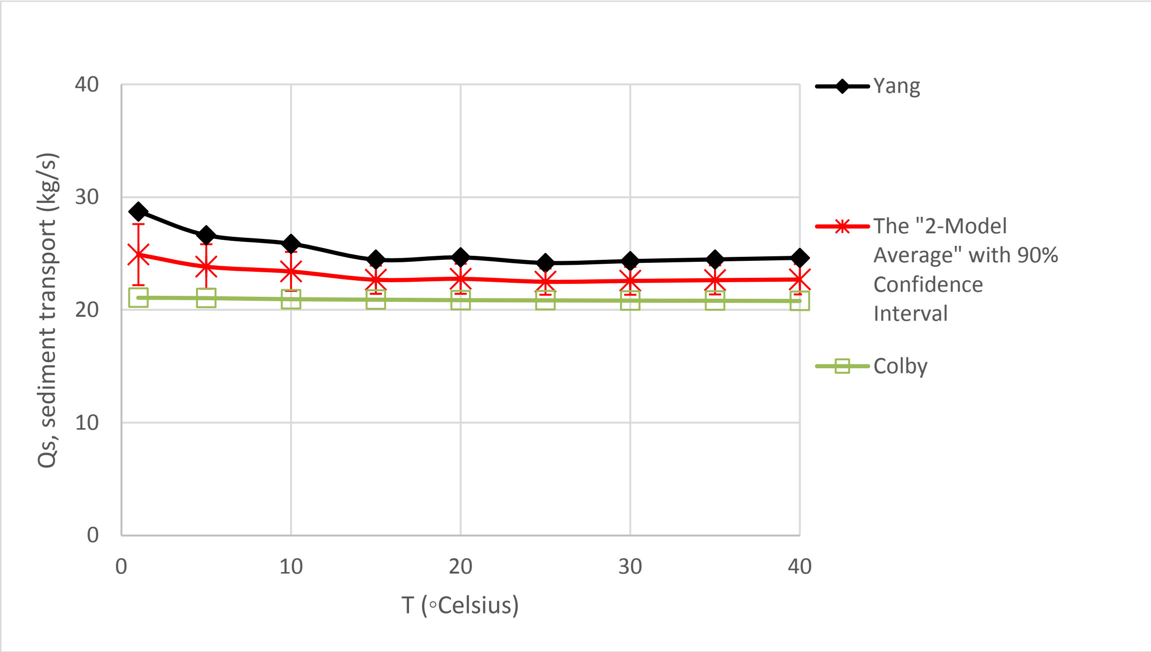

Figure 10. Effect of water temperature on sediment transport for Yang and Colby Methods. The "2-model average" with 90% confidence intervals ranging from 18% to 9% as temperature warms are shown in red.

5.3.2 Normalized Values: 2-model average

The values of all sediment outcomes were normalized exactly like the 5-model average method. See Section 5.2.2 for further explanation. The normalized results are shown in Figure 11. The "2-model average" is denoted by the red line. The corresponding tabular values are located in the Appendix, Tables A.5, A.6, and A.7.

5.3.3 Curve Fit Equation: 2-model average

Table Curve 2D software (Systat Software Inc., 2015) was used to determine a curve-fit equation for the average line using Yang and Colby's methods. The software output 100 curve-fit equations and ranked them all based on precision. The first ranked equation was selected, based on the correlation coefficient, R^2, value equal to 0.9722. The curve-fit line for this analysis is denoted as the "2-model average".

The "2-model average"equation is expressed in the following form:

$$\frac{C_t}{C_{tmax}} \, or \, \frac{Q_s}{Q_{smax}} = 0.9054 + 0.1139 \exp\left(\frac{-\frac{T}{T_{max}}}{0.1732}\right)$$

Where,

C_t = Sediment concentration (ppm) normalized over the maximum sediment concentration, C_{tmax}

Q_s = Sediment transport rate (kg/s) normalized over the maximum sediment transport rate, Q_{smax} and

T = Temperature (◦C) normalized over the maximum temperature, T_{max}.

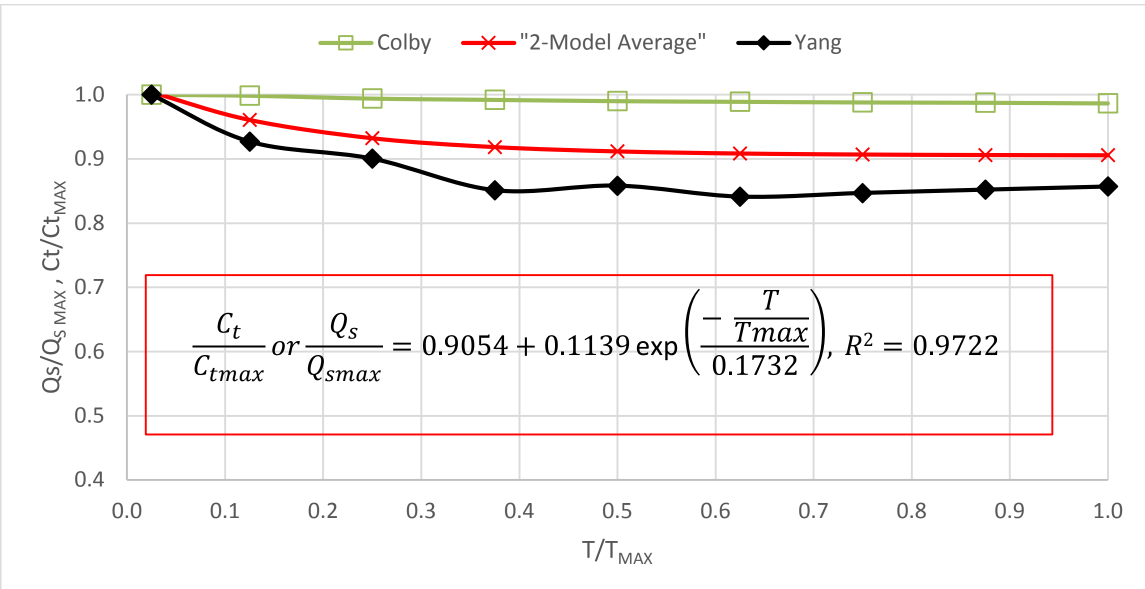

Figure 11. The effect of water temperature on sediment concentration and transport rate for Yang and Colby Methods, including the "2-model average" All values normalized.

CHAPTER 6. DISCUSSION AND FUTURE WORK

Since many of the models employed here are based on laboratory data, it is unclear if these results will be representative of field conditions. The Colby and Yang Methods, however, were based, at least partly, on field data. The Colby and Yang Methods indicate a 1.36% and 16.70% decrease in sediment transport rate, which can be considered significant and, therefore, worthy of further study. The method with the highest transport rate change was the Laursen Method with a 133.75% decrease. Further research is necessary on other field applications for the further refinement of this important topic.

6.1 Percent change in sediment results from 1 to 40 °Celsius

Table 5 shows the percent change in model predictions, for each method, over the full temperature range from 1 to 40 °C. The percent change is negative due to the decreasing trend. The "2-model average" yields a 9.67% change and the 5- model average yields a 25.10% change over the temperature range from 1° to 40 °Celsius. Colby's method suggests the smallest overall change in sediment transport potential, decreasing by 1.36%, whereas Laursen's approach predicts the largest change in the sediment transport potential, decreasing by 134%, over the full temperature range studied. Yang's method predicts a 16.7% change, Shen and Hung's a 24.66% change, and Bagnold a 28.75% change over the temperature range from 1-40 °C.

Table 5. Percent change in sediment results, by method, over the full temperature range from 1-40 °Celsius.

Method	% Change over 1 to 40 °Celsius	
Colby	-1.36%	Decrease
2-Model Average	-9.67%	Decrease
Yang	-16.70%	Decrease
Shen & Hung	-24.66%	Decrease
5-Model Average	-25.10%	Decrease
Bagnold	-28.75%	Decrease
Laursen	-133.75%	Decrease

6.2 Percent change in sediment results at 5° temperature increments

Current research (Stewart et al., 2014; Ficklin et al., 2014) predicts that stream temperatures could change from 1 to 5 °C under GCC conditions. Figure 12 shows the "5-model average" percent change in sediment results at 5° water temperature increments. The percent change is negative due to the decreasing trend. The "5-model average" predicted the largest drop in sediment transport at 5.63% from 1 to 5°C, whereas the lowest drop (1.57%) occurred from 35 to 40°C. The "5-model average" curve-fit produces an equation that shows an inverse 0.5 power relationship, between normalized values of water temperature and the sediment results (concentration and transport rate). The equation is boxed in red in Figure 12.

Figure 12 is useful for understanding at what water temperature range the largest changes in sediment yields occur. For example, if a river with similar characteristics to the Niobrara River (shown in Table 4) has an average water temperature of 10 °C (see [a] below) and the anticipated change in temperature is to 15 °C (see [b] below), the sediment transport could decline by roughly 3%. The corresponding numerical values are provided in Table A.8 in the Appendix.

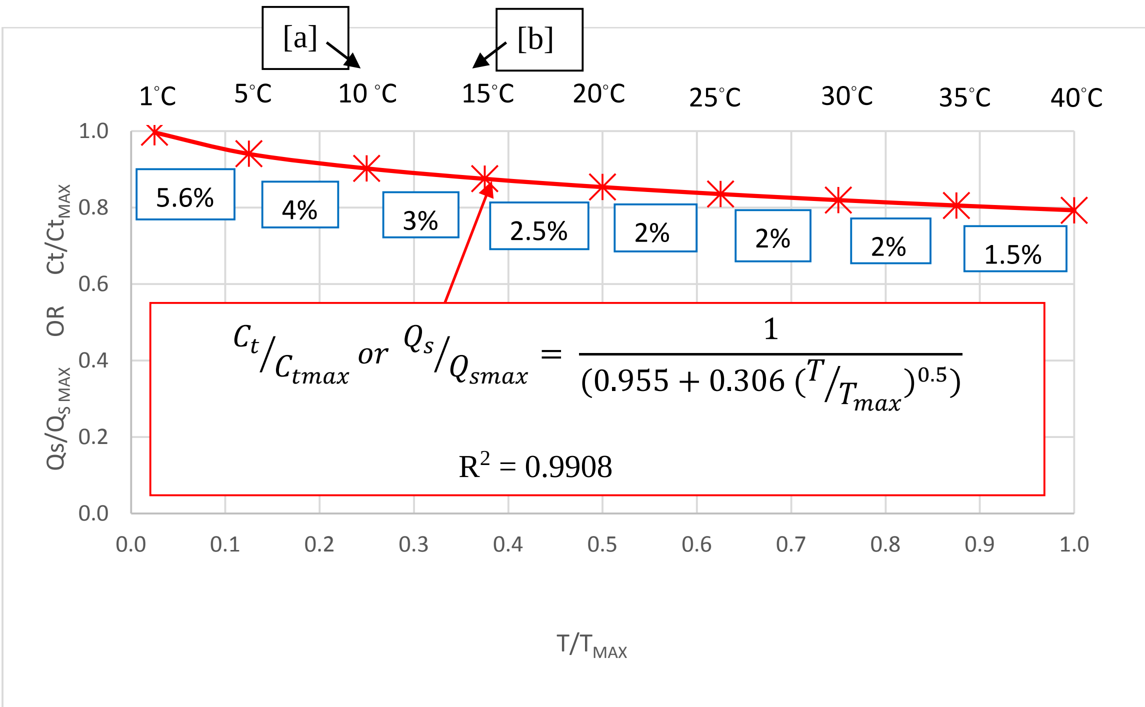

Figure 12. Percent change in the "5-model average" sediment results for each 5° increment of water temperature. The decreasing percent change is boxed in blue. [a] and [b] represent an example given in the text.

Figure 13 represents the "2-model average" percent change in sediment transport at water temperature increments of 5 °C. The percent change is negative due to the decreasing trend. The highest drop in sediment is 4.3% occurring between 1 to 5 °C, whereas the lowest sediment decline is 0.04% from 35 to 40°C. The "2-model average" curve-fit equation produces an exponential inverse relationship, between normalized values of water temperature and the sediment results (concentration and transport rate). The equation is boxed in red in Figure 13.

Figure 13 is useful for understanding at what water temperature range the largest changes in sediment yields occur. For example, if a river with characteristics similar to the Niobrara River (shown in Table 4) has an average water temperature of 5 °C (see [a] below) and the anticipated temperature change is to 10 °C (see [b] below), the sediment results could decline by roughly 3%. The corresponding numerical values are provided in Table A.8 in the Appendix.

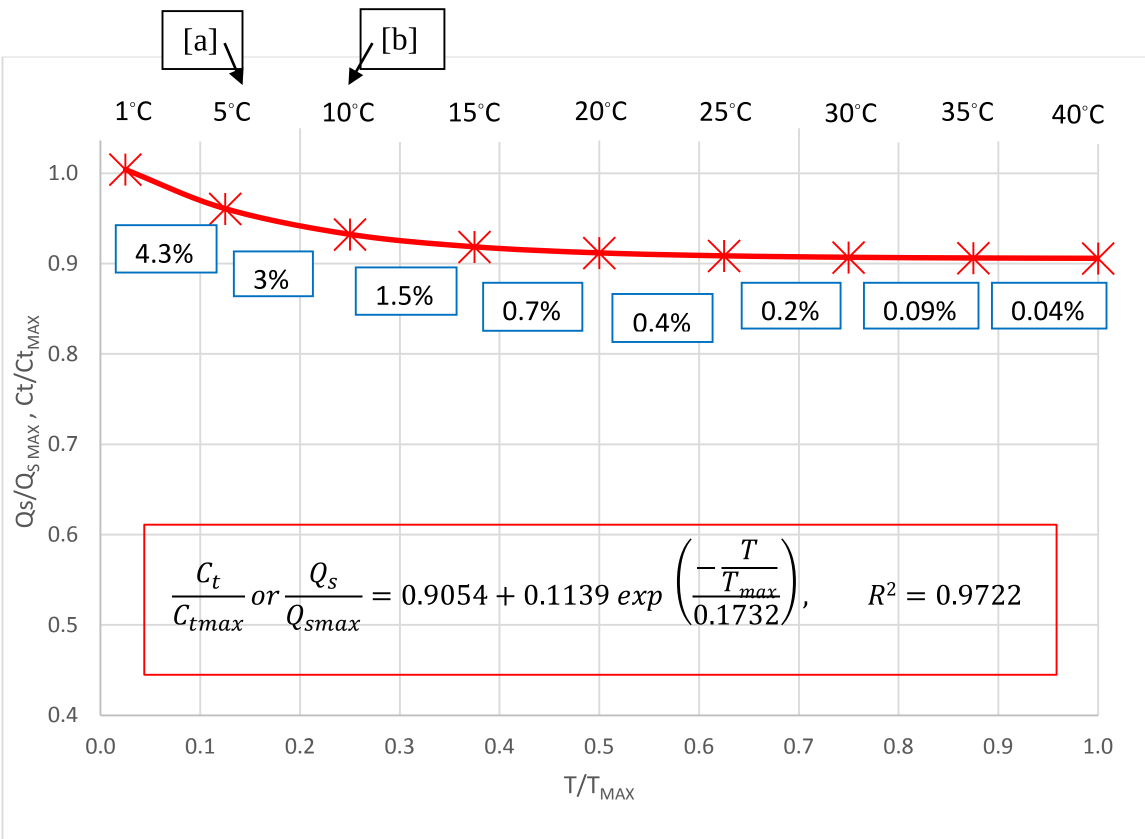

Figure 13. Percent change in the "2-model average" sediment results for each 5 increment of water temperature. The decreasing percent change is boxed in blue. [a] and [b] represent an example given in the text.

6.3 Physical Explanation of Declining Sediment Transport with Increasing Temperature

The results show that increasing water temperature, all other variables remaining constant, yields a drop in in-stream sediment transport potential due to a drop in fluid viscosity. No particle can remain suspended unless at least some of the turbulence has upward velocity exceeding the fall velocity of the particle (Bagnold, 1966). This is better understood with suspended load, where less viscous fluid will result in particles settling faster out of suspension. However, how does water viscosity effect bed-load movement? Bed-load is governed by a friction force or shear stress on the bottom boundary layer. Shear stress is expressed as:

$$\tau = \mu \frac{dV}{dy}$$

Where τ = shear stress,

μ = dynamic viscosity = ρ (fluid density) * ν = (kinematic viscosity), and

$\frac{dV}{dy}$ = Velocity gradient.

In all methods calculated, the velocity gradient is held constant. The dynamic viscosity is directly related to kinematic viscosity, which is temperature dependent. Looking at the equation, as water warms and viscosity decreases, the shear stress also decreases, resulting in less bed-load movement.

6.4 Further Investigation

Depending on the particle size, temperature will have different effects on the sediment movement. The effect of temperature for sediment particles roughly 1mm or larger (sand and gravel) will be controlled by more turbulent forces rather than by viscous forces (Colby, 1964). Although the major mechanism for sediment transport is primarily bed-load, this study considered total load, inclusive of suspended load. This work implies that suspended load, or turbidity, should also decrease as water temperature warms. By how much warrants further examination and is beyond the scope of this work. Since turbidity is a water quality concern (Chaplot, 2007; Davies-Colley, 2001) in many locations, further investigation and future work is recommended. Likewise, because thermal effects are primary survival concerns for aquatic species (D.J. & al., 2010), looking at data from other regional rivers of different sizes to show what relevant water temperatures are warrants further investigation.

CHAPTER 7. CONCLUSION AND RECOMMENDATIONS

This study documents the effect of water temperature on in-stream sediment concentration and sediment transport rate. After analyzing six sediment transport models, the results indicate that sediment transport is sensitive to changes in water temperature. The results yield a wide range of variability among the selected methods due to different parameters, however, the trend is an overall decrease in sediment concentration and transport rate as water temperature warms.

The effects of water temperature on sediment transport are small, under 6%, over the range of temperature change expected due to climate change, anywhere from 1 to 5°C. The greatest percent change in sediment transport is predicted to occur at colder water temperatures, from 1 to 5°C. As water warms, the overall percent change continues to decline. The magnitude of sediment response over the full temperature range studied from 1 to 40°C is significant depending on the method. The percent change in sediment results range from roughly 1% to 134%.

Two curve-fit equations were produced using the normalized values of water temperature to calculate sediment results. One is the 5-model average, which yields an inverse 0.5 power relationship and the second is a 2-model average, which yields an exponential inverse correlation. Suggestions for using these two model equations are below.

Additionally, this study provides a useful procedure that could help decision-makers better plan for in-stream sediment management in light of climate change. In order for river managers to "estimate or predict" the potential sediment transport in streams as a function of water temperature fluctuations, we propose three different approaches:

- If river data are known:

    1) Use Table 4 to identify which sediment transport method(s) encompass the river parameters. If only one method applies, use the corresponding sediment transport equation provided in Chapter 3. If more than one method applies, follow the demonstration procedure outlined in Chapter 4 as applied on the Niobrara River.

- If river data are unknown:

2) And the river in question has characteristics similar to those of the Niobrara River (shown in Table 2), river managers could:
    a. Use the 5-model average equation or the percent change (see Figure 12); with the understanding that this is a mix of parameters (shown in Table 4) under both lab and field testing. OR
    b. Use the 2-model average equation or the percent change (see Figure 13); with understanding that the data are from both lab and field testing (shown in Table 4). OR

3) For a more conservative approach, river managers could use the method that best fits the conditions of concern.
    a. For example, if bed degradation, bank collapse, erosion, fish habitat, or blocked harbors are of concern, use the method that yields the highest sediment transport predictions, the Shen and Hung method (see Chapter 3).
    b. Conversely, if aggradation or flooding are conditions of concern, use the method that yields the lowest sediment transport potential, Bagnold's method (see Chapter 3).
    c.

The "5-model average," the "2-model average," and the percent change presented here are simple methods to estimate the in-stream sediment transport potential. Results should hold true on rivers with similar characteristics to those of the Niobrara River, with the full realization that this is new and comparatively untested models. River managers could use the equations or percent change to roughly estimate or forecast the sediment transport potential as a result of changing water temperature that they think may occur under climate change conditions for a river with similar characteristics (shown in Table 4). Similarly, the demonstration procedure outlined in Chapter 4 could be used on rivers with similar characteristics as those shown in Table 4. Application of these models and procedures to real rivers is encouraged with caution until replicate tests are conducted.

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APPENDIX: TABULAR RESULTS

Table A.1. Temperature and corresponding kinematic viscosity of water and sand particle fall velocity, in SI units and US. Data from table A.1 corresponds to Figures 2 and 3 in the text.

TEMP (°C)	Kinematic Viscosity (m^2/sec)	Kinematic Viscosity (ft^2/sec)	Fall Velocity (cm/sec)	Fall Velocity (ft/sec)
1.0	0.000001786	0.00001920	2.90	0.0951
5.0	0.000001518	0.00001640	3.20	0.1050
10.0	0.000001306	0.00001410	3.40	0.1115
15.0	0.000001139	0.00001230	3.70	0.1214
20.0	0.000001003	0.00001080	3.80	0.1247
25.0	0.000000893	0.00000961	4.00	0.1312
30.0	0.000000801	0.00000862	4.10	0.1345
35.0	0.000000723	0.00000779	4.20	0.1378
40.0	0.000000658	0.00000708	4.30	0.1411

Table A.2. Results of sediment concentration (ppm) for all methods. "5-model average" calculation does not include Ackers & White method. Data from table A.2 corresponds to Figures 4, 5, 6, and 7 in the text.

Temp (◦C)	Yang	Ackers & White	Colby	Shen & Hung	Bagnold	Laursen	"5-model average"
1	2234.25	1923.08	1639.82	2734.38	582.45	1158.35	1669.85
5	2071.03	2127.22	1637.38	2589.52	544.99	992.87	1567.16
10	2011.59	2299.22	1630.07	2503.64	523.70	912.92	1516.38
15	1901.66	2433.20	1626.82	2387.92	496.07	784.79	1439.45
20	1917.61	2541.32	1623.57	2352.38	487.83	752.76	1426.83
25	1879.21	2622.19	1621.94	2285.30	472.58	651.63	1382.13
30	1892.08	2683.92	1620.32	2253.59	465.52	616.70	1369.64
35	1903.58	2729.90	1619.51	2223.00	458.79	554.56	1351.89
40	1914.49	2763.40	1617.88	2193.47	452.38	495.93	1334.83

Table A.3. Results of sediment transport rate (kg/s) for all methods. "5-model average" does not include Acker's & White method. Data from table A.3 corresponds to Figures 4, 5, 6, and 7 in the text.

Temp (◦C)	Yang	Ackers & White	Colby	Shen & Hung	Bagnold	Laursen	"5-model average"
1	28.73	24.73	21.09	35.16	7.49	14.90	21.47
5	26.63	27.35	21.06	33.30	7.01	12.77	20.15
10	25.87	29.57	20.96	32.19	6.73	11.74	19.50
15	24.45	31.29	20.92	30.71	6.38	10.09	18.51
20	24.66	32.68	20.88	30.25	6.27	9.68	18.35
25	24.17	33.72	20.86	29.39	6.08	8.38	17.77
30	24.33	34.51	20.84	28.98	5.99	7.93	17.61
35	24.48	35.10	20.83	28.59	5.90	7.13	17.38
40	24.62	35.54	20.80	28.21	5.82	6.38	17.16

Table A.4. Sediment concentration (ppm) results for the "5-model average" (mean), the standard deviation calculated over five methods (excluding Ackers & White), and the 90% confidence intervals. Data from table A.4 corresponds to Figures 6 and 7 in the text.

Temp (◦C)	"5-model average"	Standard Deviation over five methods	90% Confidence Interval	Percentage of Confidence about the Mean
1	1669.85	761.15	559.95	33.53
5	1567.16	731.94	538.46	34.36
10	1516.38	718.67	528.70	34.87
15	1439.45	702.41	516.74	35.90
20	1426.83	703.18	517.31	36.26
25	1382.13	704.45	518.24	37.50
30	1369.64	707.32	520.35	37.99
35	1351.89	716.68	527.24	39.00
40	1334.83	726.07	534.14	40.02

Table A.5. Sediment transport rate (kg/s) results for the "5-model average" (mean), the standard deviation calculated over five methods (excluding Ackers & White), and the 90% confidence intervals. Data from table A.5 corresponds to Figures 6 and 7 in the text.

Temp (◦C)	"5-model average"	Standard Deviation over five methods	90% Confidence Interval	Percentage of Confidence about the Mean
1	21.47	9.79	7.20	33.53
5	20.15	9.41	6.92	34.36
10	19.50	9.24	6.80	34.87
15	18.51	9.03	6.64	35.90
20	18.35	9.04	6.65	36.26
25	17.77	9.06	6.66	37.50
30	17.61	9.10	6.69	37.99
35	17.38	9.22	6.78	39.00
40	17.16	9.34	6.87	40.02

Table A.6. Normalized values obtained by dividing each sediment outcome by the maximum sediment result and each temperature by the maximum temperature. Data from Table A.6 corresponds to Figure 8 in the text.

Temp (◦C)	Yang	Colby	Shen & Hung	Bagnold	Laursen
1	1.00	1.00	1.00	1.00	1.00
5	0.93	1.00	0.95	0.94	0.86
10	0.90	0.99	0.92	0.90	0.79
15	0.85	0.99	0.87	0.85	0.68
20	0.86	0.99	0.86	0.84	0.65
25	0.84	0.99	0.84	0.81	0.56
30	0.85	0.99	0.82	0.80	0.53
35	0.85	0.99	0.81	0.79	0.48
40	0.86	0.99	0.80	0.78	0.43

Table A.7. Normalized values for the average of all sediment concentration (ppm) methods obtained by dividing each result by the maximum sediment result and each temperature by the maximum temperature. Data from table A.7 corresponds to Figure 8 in the text.

Average (ppm)	Ct/Ct_{max}	T/T_{max}
1669.849	1.000	0.025
1567.161	0.939	0.125
1516.384	0.908	0.250
1439.451	0.862	0.375
1426.830	0.854	0.500
1382.131	0.828	0.625
1369.641	0.820	0.750
1351.887	0.810	0.875
1334.830	0.799	1.000

Table A.8. Normalized values for the average of all sediment transport (kg/s) methods obtained by dividing each result by the maximum sediment result and each temperature by the maximum temperature. Data from table A.8 corresponds to Figure 8 in the text.

Average (kg/s)	Q_s/Q_{smax}	T/T_{max}
21.47	1.000	0.025
20.15	0.939	0.125
19.50	0.908	0.250
18.51	0.862	0.375
18.35	0.854	0.500
17.77	0.828	0.625
17.61	0.820	0.750
17.38	0.810	0.875
17.16	0.799	1.000

Table A.9. Results of sediment concentration (ppm) for the two methods that encompass all Niobrara River characteristics. The "2-model average" (mean of Yang and Colby method), the standard deviation, and the 90% confidence intervals also shown. Data from Table A.9 correspond to Figures 9 and 10 in the text.

Temp (◦C)	Yang	Colby	"2-Model Average"	Standard Deviation over two methods	90% Confidence Interval Range	Percentage of Confidence about the Mean
1	2234.25	1639.82	1937.04	297.22	345.72	17.85
5	2071.03	1637.38	1854.21	216.83	252.21	13.60
10	2011.59	1630.07	1820.83	190.76	221.89	12.19
15	1901.66	1626.82	1764.24	137.42	159.84	9.06
20	1917.61	1623.57	1770.59	147.02	171.01	9.66
25	1879.21	1621.94	1750.58	128.63	149.62	8.55
30	1892.08	1620.32	1756.20	135.88	158.06	9.00
35	1903.58	1619.51	1761.54	142.04	165.22	9.38
40	1914.49	1617.88	1766.19	148.31	172.51	9.77

Table A.10. Sediment transport rate (lg/s) results for Yang, Colby and the "2-model average." These methods encompass all Niobrara River characteristics. Table A.10 corresponds to Figure 10 in the text.

Temp (◦C)	Yang	Colby	"2-Model Average"
1	28.73	21.09	24.91
5	26.63	21.06	23.84
10	25.87	20.96	23.41
15	24.45	20.92	22.69
20	24.66	20.88	22.77
25	24.17	20.86	22.51
30	24.33	20.84	22.58
35	24.48	20.83	22.65
40	24.62	20.80	22.71

Table A.11. 2-model average results for sediment concentration and transport rate. Normalized values for Yang, Colby, Sediment concentration (Ct), Sediment Transport (Qs) and Temperature. Data from Table A.11 relates to Figure 11 in the text.

Temp (◦C)	"2-model average" (ppm)	"2-model average" (kg/s)	Yang	Colby	Ct/Ctmax or Q_s/Q_{smax}	T/Tmax
1	1937.04	24.91	1.00	1.00	1.000	0.025
5	1854.21	23.84	0.93	1.00	0.957	0.125
10	1820.83	23.41	0.90	0.99	0.940	0.250
15	1764.24	22.69	0.85	0.99	0.911	0.375
20	1770.59	22.77	0.86	0.99	0.914	0.500
25	1750.58	22.51	0.84	0.99	0.904	0.625
30	1756.20	22.58	0.85	0.99	0.907	0.750
35	1761.54	22.65	0.85	0.99	0.909	0.875
40	1766.19	22.71	0.86	0.99	0.912	1.000

Figure 1 documentation requested by Graduate School at Michigan Technological University. Obtained from FAQ at https://www.climate.gov/faqs#hide3