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Abstract:

Rivers are unique ecosystems that are constantly under risk of being overused and degraded to a point where native species are put at risk. In order to best protect species, it is important to understand the microhabitats that they depend on. This study examines the impact of waterfalls on dissolved oxygen, water temperature, turbidity, and stream velocity, and the impact of these habitat characteristics on fish diversity at various locations upstream and downstream from the falls on the Big Sioux River in Sioux Falls, South Dakota. Habitat conditions were found to be significantly different (p<0.05) when comparing upstream and downstream conditions for all of the characteristics except water temperature. Dissolved oxygen and velocity were found to be higher downstream than upstream, while water clarity was found to be lower downstream (indicating a higher turbidity). Fish diversity was found to be higher upstream from the waterfall, however, not at a statistically significant level. Velocity was found to have the greatest impact on determining the diversity of fish at a particular location.

Introduction:

Rivers are often taken for granted by humans because they can be found with relative ease throughout much of the world. In reality, these systems are actually quite unique when compared to other aquatic ecosystems. Only about 0.006% of all freshwater or about 0.0002% of all water on earth is found in rivers (United States Geological Survey 2016). Despite the relative rarity of rivers compared to other sources of water, rivers are important features in human life because they provide numerous commodities including drinking water, recreation, food, and transportation.

The great demand for the use of rivers by humans can introduce many threats to natural river ecosystems. One example of a threat to rivers that causes concern is the overuse of water for irrigation and drinking water, which can physically take away the water that a riverine ecosystem needs to function. Another example of threats to river ecosystems is that rivers have historically been used to carry away pollution with an “out-of-sight, out-of-mind” mentality, which gives little to no consideration for the aquatic habitat conditions downstream and can
lead to the creation of anoxic habitat conditions resulting in large-scale fish kills. Dams can also create a variety of threats to riverine ecosystems by preventing fish migration further upstream, trapping sediment, and altering river flows that could put biodiversity in native ecosystems at risk.

Biodiversity is important in ecosystems for a variety of reasons, ranging from economic to environmental. From an agricultural perspective, one of the greatest economic benefits from a diverse ecosystem is a greater protection from environmental extremes, such as drought. A more diverse ecosystem includes a wider variety of plants, some of which are likely to be more drought tolerant than others. Therefore, if a drought strikes, the more drought tolerant plants could still survive and provide food, while if it were an ecosystem with low biodiversity, such as a monoculture, nearly all of the plants could be eliminated by the drought. Along those same lines, more diverse ecosystems are better able to recover from any sort of disturbance because the species have different tolerances to disturbances. Biodiversity is also important because it provides humans with various resources, such as food, medicine, and raw materials that are required for everyday life. When considering the importance of biodiversity, it becomes clear that it should be protected as best as possible, especially in unique ecosystems, such as rivers.

In order to best protect biodiversity in river ecosystems, it is important to understand which habitats of a river have the greatest biodiversity in order to adequately protect species. One natural landform that could create unique microhabitat conditions in rivers is waterfalls. These unique microhabitats could have the possibility of housing unique species better suited to the harsher environment below a waterfall. However, the impacts of waterfalls on habitat
conditions have been examined in relatively few studies. Waterfalls have the obvious impact of preventing fish from moving further upstream, but they could also have potential impacts on physical and chemical characteristics of a river as well. These potential differences in the characteristics of the river could create microhabitats that are unique when compared to the surrounding river system. Waterfalls also have a cultural and tourism importance which provides further incentive to improve water and river quality in those areas. While waterfalls have been occasionally studied from cultural and tourism aspects, relatively few studies have been done on the impact of waterfalls on river characteristics and fish diversity (Clayton and Pearson 2016). Therefore, this study will attempt to address how waterfalls affect river characteristics and the impact those differences have on fish diversity upstream and downstream from the waterfall.

**Problem Statement:**

Aquatic habitat conditions downstream of waterfalls are able to sustain a higher diversity of fish species when compared to upstream from waterfalls due to more favorable levels of dissolved oxygen, turbidity, temperature, and velocity. It is expected that most of the observed difference will be due to higher dissolved oxygen levels below the falls after the water gets churned up by falling over the rocks. Turbidity is also expected to be higher below a waterfall because the falling water is likely to erode and carry away the rock and sediments at the base of the falls. Temperature is expected to be higher below the falls because the water is expected to be flowing slower and slower-moving streams generally have a higher temperature. Finally, it is expected that the velocity will be lower below a waterfall because the
water will likely slow down after hitting and transferring its energy into the rocks and sediments in the plunge pool at the base of a waterfall.

Literature Review:

1. Waterfalls

Waterfalls have long been a source of admiration as aspects of cultural geography and tourism (Hudson 2002; Hudson 2013). One reason for the interest of cultural geographers is the barriers posed by waterfalls to transportation and travel (Hudson 2013). Some cultural geographers are also interested in the impact of waterfalls on artistic and religious aspects of different areas. However, despite the interest in waterfalls from the general public, tourism, and cultural geography standpoints, relatively little literature, especially recent research, is available on the physical processes of waterfalls and their impacts on the characteristics of rivers.

1.1. Formation

Before being able to determine the impact a waterfall may have on various characteristics of a river, it is important to consider the processes by which waterfalls form and operate. Waterfalls can form through a variety of processes. The primary process of formation is through undercutting (Chisholm 1885; von Engeln 1929; von Engeln 1940; Micalizio 2013; BBC 2014). Undercutting occurs when a river flows over a harder layer of rock that is located on top of a softer layer of rock. As water flows over the rock layers, the softer rock erodes faster than the harder layer. The softer rock then cuts under the harder layer creating an overhang
that the water flows over creating the waterfall. As the weaker rock gets eroded more and
more, the outcropping ledge of the more resistant rock becomes unstable and can fall into the
plunge pool below (Micalizio 2013; BBC 2014). This process causes most waterfalls to migrate
slowly upstream. Because waterfalls tend to form in areas with relatively hard rock layers that
are at the earth’s surface, waterfalls are often found in mountainous regions where harder
rocks that form under pressure deep in the earth’s crust get upheaved towards the earth’s
surface during the tectonic processes that create mountains (Chisholm 1885).

There are also several less common ways that waterfalls are formed. Waterfalls can
occur anywhere where a river falls over a steep gradient in the landscape. As a result, tectonic
landforms, such as fault lines, mountains, or volcanoes can also contribute to forming a
waterfall by interfering with the natural path of the river (Micalizio 2013). Glaciers are also able
to create waterfalls (von Engeln 1940; Micalizio 2013). Von Engeln describes several waterfalls
that were formed by glacial processes in the Finger Lakes region of New York (1940). The
glaciers created hanging valleys as they carved through the landscape. Once the glaciers
retreated, rivers and streams began to flow over the edges of those hanging valleys forming
waterfalls.

1.2 Impact on River Characteristics

While the formation processes of waterfalls is relatively well documented, one topic
related to waterfalls that there seems to be relatively little scientific literature on is the impact
of waterfalls on various characteristics of rivers, such as turbidity, discharge, water
temperature, and dissolved oxygen. Despite this, some information could be found about those characteristics of rivers in general that can likely be applied to waterfalls as well.

Turbidity is simply a measurement of the clarity of a liquid (Minnesota Pollution Control Agency 2008; United States Geological Survey 2016). Regarding rivers, a lack of clarity generally comes from suspended sediments in the water or dissolved compounds in the water (Minnesota Pollution Control Agency 2008). The main contribution to turbidity comes from suspended sediments that a river picks up either from overland runoff or from the bed of the river itself (Pielou 1998). Generally speaking, rivers that have a bed made up of hard rock will typically have a lower turbidity, or be clearer, while rivers that run through areas with softer rock or mostly sediment will have a higher turbidity and appear muddier (Pielou 1998). As water crashes over a waterfall, the energy from the falling water is transferred into the rock below the waterfall, which helps erode the rock and suspend the particles in the water column. Because of this, it is expected that turbidity will be greater, meaning that the water would be less clear, downstream from the falls than upstream.

A higher discharge can also increase the sediment load, and therefore turbidity, of a river (Hudson 2002). The main factors that affect the discharge of a river are the cross-sectional area (width multiplied by the height), the slope of the river, and the roughness of the channel bottom (Pielou 2008). It is not expected that discharge will differ above and below a waterfall because no water is being added or removed from the system over the relatively short distance of the waterfall. However, Micalizio found that as the slope of the river at the waterfall is greatly increased, the velocity of a river increase as the river nears a waterfall (2013). No information was available about what happens to stream velocity downstream from a waterfall.
Similar to turbidity and discharge, temperature and dissolved oxygen are also partially connected. Colder water can hold more dissolved oxygen than warmer water (Risberg 2009). Generally, shallow, slow-moving rivers will have a higher temperature than deeper, faster-moving streams (Jackson et al. 2001). At the same time these shallower, slow-moving streams usually face higher biological oxygen demand due to higher respiration and decomposition rates because of the higher temperature. The elevated biological oxygen demand uses up some of the dissolved oxygen in the water. As a result, these shallower, slow-moving streams typically have lower dissolved oxygen levels than faster moving cold water streams. Streams that have a high gradient with turbulence and surface agitation can re-aerate the water increasing the dissolved oxygen content of the water (Risberg 2009). Because of this, it would likely be expected that dissolved oxygen content would be higher below a waterfall after it was churned up and re-aerated than above a waterfall.

1.3 Barriers to Fish

Waterfalls can also have significant impacts on the organisms that live in a river. It has been well studied and documented that waterfalls act as a barrier to fish migration upstream effectively creating a natural barrier between fish populations in a stream (Rahel 2007; Northcote 2010; Torrente-Vilara et al. 2011; Barbosa et al. 2015; Baker et al. 2017). These barriers have the potential to create unique biota above and below the falls (Torrente-Vilara et al. 2011; Barbosa et al. 2015; Baker et al. 2017). Once an individual has been washed over the edge of the waterfall, it becomes permanently removed from the upstream community (Northcote 2010). Covich et al. found that in the tropics, fish diversity is higher in below
waterfall pools than above waterfall pools, however, this study did not examine the potential changes in habitat conditions due to the waterfall (2009). Baker et al. found that waterfalls higher than six meters in height effectively blocked all passage of fish (2017). While this initially seems like a large height for a fish to overcome, Baker et al. reported the presence of some species of fish (*Gastromyzon*) in Borneo that have a suckermouth and modified pectoral and pelvic fins that allow them to climb almost vertical rocks. This likely means that the height of a waterfall could be lower and still effectively block most species of fish. Despite the seemingly impassable barrier of a waterfall, it is possible for fish to get around them with the intervention of humans.

Rahel presents the idea that aquatic systems are becoming more homogenous because humans provide species with ways to get around traditional barriers (2007). This may occur through a variety of ways such as stocking lakes and rivers with certain species of fish, through the unintentional introduction of a hitchhiking invasive species, or through providing some sort of bypass around the waterfall such as a canal. This could indicate that while waterfalls were historically significant barriers to fish populations, they may pose less of a barrier and impact in today's world where humans have heavily modified the environments around them.

2. **Environmental Tolerances of Fish**

All of these characteristics of a river can affect the suitability of the river as a habitat for fish. Hutchinson’s idea of an ecological niche states that species tend to occupy the areas in which the biotic and abiotic conditions give them the best chance for the survival and reproduction of that species (Barbosa et al. 2015). A variety of factors can affect the range that
a species can live in with the main factors being temperature, stream velocity, and dissolved oxygen levels (Jackson et al. 2001). One of the critical aspects of determining where fish will be found, especially among microhabitats, is dissolved oxygen. Coble found that at locations in a river where the average dissolved oxygen levels in the summer were greater than 5 mg/liter, a higher number of fish species were present than at locations where dissolved oxygen levels were below 5 mg/liter (1982). The lethal level of dissolved oxygen varies among fish species, but is generally below 3.0 mg/liter (Doudoroff and Shumway 1970). In general, the minimum level of dissolved oxygen needed for a healthy fish population is 5.0 mg/l (Edwards 1983).

3. Study Area: Big Sioux River

This study will focus on the falls of the Big Sioux River in southeastern South Dakota. The Big Sioux River begins in northeastern South Dakota near Summit and flows south for approximately 420 miles (676 km) into the Missouri River near Sioux City, Iowa (Jorgensen and Ackroyd 1973; East Dakota Water Development District 2018) (Figure 1). The river flows through a relatively well-defined meandering channel with an average gradient of approximately 2.6 feet per mile, except near Sioux Falls (Ellis, Adolphson, and West 1969, Jorgensen and Ackroyd 1973). Many of the tributary streams that flow into the Big Sioux River are intermittent and generally only flow in the spring following the snow melt or during periods of heavy rainfall.
Figure 1: Big Sioux River and Watershed
3.1. Big Sioux River Hydrology

The drainage basin area of the Big Sioux River is approximately 9,000 square miles (23,310 km$^2$) and drains parts of eastern South Dakota, southwestern Minnesota, and northwestern Iowa (East Dakota Water Development District 2018) (Figure 1). The basin was formed during the Wisconsin Glaciation which carved out the river valley and deposited sediments as it receded creating the Big Sioux River watershed (Flint 1955; Friends of the Big Sioux River 2017). Most of the streambed is made up of permeable silt and sand, except the Sioux quartzite formation in and around Sioux Falls. This Sioux quartzite is the foundation for the formation of the falls and will be discussed in the following section.

The Big Sioux River is an important source of water for several cities in eastern South Dakota, especially Sioux Falls (Jorgensen and Ackroyd 1973; Rambow 1999). The river is hydraulically connected to an aquifer in the region around Sioux Falls, which provides base flow to the river in times of low flow and is recharged by the river in times of higher flow (Jorgensen and Ackroyd 1973). The average annual discharge of the river is approximately 250 cubic feet per second (cfs) (7.8 m$^3$/s).

3.2 Formation of the falls of the Big Sioux River

The creation of the falls on the Big Sioux River was likely similar to the undercutting process described above. As the river flows through Sioux Falls, it flows over alternating strata of softer rocks and the sediments that were deposited by glaciers during the Wisconsin Glaciation and harder quartzite bedrock that was exposed during the same glaciation event but formed much earlier (Jarrett 1994; Rambow 1999; South Dakota Department of Tourism 2009).
The hard quartzite bedrock was first created over a billion years ago in the Precambrian era (Flint 1955; Jarrett 1994; South Dakota Department of Tourism 2009). The quartzite started as sand that was deposited on the floor of an ancient seabed (Rambow 1999; South Dakota Department of Tourism 2009). As the layers of sand that were deposited started to build up, the lower layers were put under immense heat and pressure, causing the rocks to metamorphose forming the quartzite seen today (Rambow 1999). The resulting quartzite is extremely hard and very resistant to weathering and erosion (Jarrett 1994).

As the river flows over these alternating layers of hard quartzite and softer rocks, the river began to erode the softer layers faster than the hard quartzite. This process created a nickpoint over which the water plunged, forming the falls of the Big Sioux River. Figure 2a shows a diagram of this process of waterfall formation. Today, the falls drop approximately 100 feet (30.5 meters) in less than half a mile (0.8 km) (Rambow 1999; Visit Sioux Falls 2018) with an average of 7,400 gallons (28,012 liters) of water flowing over the falls every second (Visit Sioux Falls 2018).

Figure 2: (a) Diagram of waterfall formation, (b) Falls of the Big Sioux River (Figure 11.20 from Elemental Geosystems)
3.3 Use of the Falls by the City of Sioux Falls

Rivers are widely used by humans, and the Big Sioux River and the falls on the river are no exception. Since the city of Sioux Falls was founded in 1856, the falls have been a center point for the city from both a cultural and industrial aspect (Rambow 1999; Visit Sioux Falls 2018). As a result of the industrial goals in the early part of the city’s history, several attempts were made to alter the flow of the river over the falls to maximize and harness the current for industrial purposes. In 1880 and 1881, a small dam was built to power the large Queen Bee Flour Mill that was constructed along the river near the falls (Rambow 1999). However, the mill never succeeded and closed in 1883 partially due to a short supply of wheat and a lack of water to power such a large mill (Rambow 1999; Visit Sioux Falls 2018). These problems were both caused by a drought that occurred around the same time that the mill opened (Rambow 1999).

Following the failure of the mill, a hydroelectric power plant was constructed in 1908 by using and enhancing the existing dam (Rambow 1999; Visit Sioux Falls 2018). Around the same time, a channel that flowed around an island upstream of the falls was closed off to increase flow through the main channel providing a stronger current for the hydroelectric generators. The hydroelectric plant was decommissioned in 1972 and donated to the city in 1977. The dam has been partially removed since then allowing that part of the river to partly return to its natural flow pattern in that area (Rambow 1999). The falls are now incorporated into the Sioux Falls parks system as part of the 123 acre Falls Park located north of downtown Sioux Falls (Visit Sioux Falls 2018).
A dam and diversion channel were built in the late 1950s to help manage and control flooding in the area from the Big Sioux River (National Weather Service). The dam and the start of the diversion channel were built north of the Sioux Falls Regional Airport and reconnected with the main river channel after flowing down the spillway a little under a mile downstream from the falls. The dam and diversion channel reduce the amount and velocity of water that flows through the central part of the city and over the falls, especially during high precipitation events.

3.4 Water Quality Requirements of the Big Sioux River

The Big Sioux River has been designated as a Warmwater Semipermanent Fish Life Propagation waterbody by the State of South Dakota (City of Sioux Falls). The Administrative Rules of South Dakota (ARSD) define Warmwater Semipermanent Fish Life Propagation waters as water bodies that are able to “support aquatic life and are suitable for the propagation or maintenance, or both, of warmwater fish but may suffer occasional fish kills because of critical natural conditions” (74:51:01:01). Several water quality requirements have been set to meet this designation. Dissolved oxygen levels must be higher than or equal to 5.0 mg/L, the temperature must remain below 90°F (approximately 32°C), pH must stay between 6.5 and 9.0, and total suspended solids cannot exceed 158 mg/L in a single day (ARSD 74:51:01:48).

3.5 Fishes in the Big Sioux River near Sioux Falls

In 1967, James Sinning sampled the fish communities of the Big Sioux River at 13 locations along the course of the river. At a location north of Sioux Falls, the three most
commonly found fish species were sand shiner (*Notropis stramineus*), red shiner (*Cyprinella lutrensis*), and common carp (*Cyprinus carpio*) (Sinning 1968). At this location, a total of 15 species were found. At a location three miles (4.8 km) east of Sioux Falls, common carp, red shiner, and black bullhead (*Ameiurus melas*) were the most commonly found fish species. At this location, a total of 11 species were found. The same 13 sites were later sampled again by Dieterman and Berry and found that the average species richness was higher in 1994 than in 1967 (1998). However, Dieterman and Berry do not specify which species were caught at each site, so there is no way to directly compare how the two locations near Sioux Falls had changed since 1967.

The South Dakota Game, Fish, and Parks (SDGFP) have also historically stocked the river in Minnehaha County with some species, mainly game fish. The most recent record of fish being stocked into the river was in 1995 when some black bullhead and yellow perch (*Perca flavescens*) were added to the river (SDGFP).

4. **Hypotheses**

   **General:**

   \[ H_0: \text{Habitat conditions will be the same or worse for fish diversity downstream from a waterfall than upstream from a waterfall.} \]

   \[ H_1: \text{Habitat conditions will be better for fish diversity downstream from a waterfall than upstream from a waterfall.} \]

   **Rationale:** The changes in the characteristics of the river, especially the higher dissolved oxygen levels that are expected will make the river habitable for a
wider range of fish below the waterfall than above the waterfall where the
different habitat conditions may exclude some fish from surviving there.

**Dissolved Oxygen:**

**H₀:** Dissolved oxygen levels are either the same or lower downstream from a
waterfall than upstream from a waterfall.

**H₁:** Dissolved oxygen levels are greater downstream from a waterfall than
upstream from a waterfall.

**Rationale:** Surface agitation of water through waterfalls and rapids can allow
oxygen to be dissolved into water (Risberg 2009).

**Temperature:**

**H₀:** Temperature will either be the same or lower downstream from a waterfall
than upstream from a waterfall.

**H₁:** Temperature will be higher downstream from a waterfall than upstream
from a waterfall.

**Rationale:** The temperature of a slower-moving stream tends to be higher than a
faster-moving stream (Jackson et al. 2001). Therefore, it is expected that the
temperature would be higher below the waterfall after the water has slowed
down after going over the falls.
Turbidity:

H₀: Turbidity will be either the same or lower (indicating clearer water) downstream from a waterfall than upstream from a waterfall.

H₁: Turbidity will be higher downstream from a waterfall (indicating less clear water) than upstream from a waterfall.

Rationale: Waterfalls also contribute greatly to erosion at the base of the waterfall and in the plunge pool, therefore, it is likely that the turbidity of the river would likely be greater below the waterfall.

Velocity:

H₀: River velocity will be either the same or higher downstream from a waterfall than upstream from a waterfall.

H₁: River velocity will be lower downstream from a waterfall than upstream from a waterfall.

Rationale: The velocity of a river increases as a river nears a waterfall (Micalizio 2013). As the water lands into the plunge pool, it will likely slow down because gravity will have less of an effect.
Methods:

1. Sampling Locations

Water characteristics of the Big Sioux River were sampled at eight locations over an approximately two-mile reach centered around Falls Park in Sioux Falls, South Dakota. The first two sampling locations were chosen directly above and directly below an offshoot waterfall of the main falls. Only samples for dissolved oxygen, temperature, and turbidity were taken at these two locations due to safety concerns of wading into the river because of the swift current.

The remaining six sampling locations were split evenly between upstream and downstream. Three sampling locations were chosen within one mile upstream of the main falls and three sampling locations were chosen within one mile downstream of the main falls (Figure 3). The first locations, both upstream and downstream, were located approximately 0.25 miles (0.4 km) away from the main falls. These two locations were chosen by being as close to the falls as possible while ensuring safety while working in the river for sampling. The second locations were located approximately 0.50 miles (0.8 km) away and the third locations were located approximately 0.75 miles (1.2 km) away from the main falls. At these six locations, samples were taken to determine dissolved oxygen, temperature, turbidity, and fish species present. The discharge and velocity were only measured at the Upstream 1 and Downstream 1 sites.
Figure 3: Sampling Locations along the Big Sioux River in Sioux Falls, SD
Dissolved oxygen, temperature, turbidity, and fish community samples were taken at each site once a week for thirteen weeks during the summer of 2018. Discharge was only measured for the last seven weeks of the sampling period due to high rain events early in the summer causing flooding and swift currents in the river which prevented safe wading in the river. Discharge sampling began once the river was able to be safely waded across. If weather prevented sampling on a particular day, samples were taken at the next available time once the weather cleared up.

2. Field Methods

Dissolved oxygen, temperature, and turbidity were recorded at all eight sampling locations. Dissolved oxygen and temperature were measured by placing a Hach dissolved oxygen probe into the water pressing the read button. The reading on the screen was then allowed to stabilize. Once the reading had stabilized, the values for dissolved oxygen and temperature were recorded. This was repeated a second time to get two readings at each site for each sampling date.

Turbidity was measured using a turbidity tube similar to the one shown in Figure 4. The procedure used for measuring turbidity was similar to that described by Myre and Shaw (2006) and the UW Extension (2006) with slight modification due to minor differences in turbidity tube design. This method actually measures water clarity, which is used as a proxy for turbidity in this study. First, the tube was submerged facing
upstream and filled completely with water from the river after ensuring that the bottom drain valve was closed. Then water was drained from the tube by opening the drain valve at the bottom while the tube was observed from approximately 10 centimeters above the tube. Once the black and white circle at the bottom of the tube could be barely seen through the water, the drain valve was closed. The height of water remaining in the tube was then measured to the nearest tenth of a centimeter. Because this method is measuring water clarity instead of turbidity, a larger measurement corresponds to more clear, or less turbid water, while a smaller measurement would indicate more turbid water.

Dissolved oxygen, temperature, and turbidity measurements were taken along the river bank at all eight sampling locations. Sampling along the river bank was chosen because sampling in the river channel was not possible at the directly above and below waterfall locations due to swift current preventing wading. Fish populations were also sampled at the six upstream/downstream sites. Discharge was only measured at the Upstream 1 and Downstream 1 sites.

Discharge was measured by using the method described by Pielou (1998). The discharge is estimated by calculating the cross-sectional area of the channel multiplied by the average stream velocity. First, the width of the river was measured and recorded in meters by running a meter tape across the channel. If the distance was greater than the 50-meter measuring tape, a marking post was placed at 50 meters and the remaining distance was measured from that post. The width was then divided into five intervals by dividing the width by six. Depth and velocity measurements were then taken at each of these locations. For example, if the width of the channel was sixty meters, depth and velocity would be measured at ten meters, twenty
meters, thirty meters, forty meters, and fifty meters. At each of the interval markers, velocity measurements were taken at six-tenths of the depth of the channel. For example, if the depth was one meter, the velocity was taken at a depth of 0.6 meters. Discharge was then calculated by multiplying the width by the average depth and the average velocity from each of the intervals. Velocity was measured using a Geopacks flow meter. The flow meter was allowed to run for one minute facing upstream before stopping. The number of signals counted by the meter after one minute was recorded. This number was then converted into velocity in meters per second using the following equation (1) provided by Geopacks where \( C \) is the number of counts in one minute:

\[
\text{Water Velocity (m/s)} = 0.000854C + 0.05 \quad (1)
\]

Discharge was not measured if water levels were too high or if the velocity was too fast to safely work in the river. Instead, discharge was estimated by correcting data from an upstream USGS Stream Gage, Station 06482000. This station was located approximately seven miles (11.3 km) upstream from the main falls. The method used to estimate discharge is described in the analytical methods section below.

Fish populations were sampled at each of the upstream and downstream sites using minnow traps with an opening of approximately one inch in diameter. Traps were baited and set once a week in the afternoon/evening and were left to sit for 18-22 hours. A variety of baits were used throughout the summer in order to attract a variety of species, but all sites had the same bait type on any specific sampling day. One trap was placed at each site each week but was not always set in the same place in the channel in order to sample from several different habitat types. All of the habitat conditions (e.g. pool/riffle and cut bank/point bar) at each site
were sampled over the summer sampling period. Traps were then picked up again in the late morning to early afternoon and any fish in the traps were placed in a bucket before being identified to species. Once an individual was identified to species it was released back into the river. The total number of each species caught at each site was recorded.

3. Analytical Methods

On days when discharge could not be measured due to high flow conditions, the discharge was estimated using corrected data from United State Geological Survey (USGS) Stream Gage Station 06482000, which is approximately seven miles (11.3 km) upstream from the main falls. First, the field collected data was compared to the USGS stream gage data for the same day. The difference between the measured upstream value and the USGS value was calculated. This was done for all days that discharge was measured in the field. Then the average difference between the measured values and the USGS values was then calculated. Finally, the average difference was then added to the reported USGS discharge values for the days that discharge could not be measured in the field to get an estimated value at the upstream sampling location. This process was then repeated for the downstream sampling location. Gage height data was estimated using the same correcting method described for discharge using the measured average depth and comparing to the USGS reported gage height. River velocity for the days that could not be measured was then estimated using the equation (2) below:

\[
\text{Estimated Velocity} = \frac{\text{Corrected Discharge}}{\text{Corrected Gage Height} \times \text{Average Measured Width}}
\] (2)
Shannon Index of Diversity was calculated to determine the diversity of fish species at each of the six upstream/downstream sites using the following formula (3) where $p_i$ is the proportion of the number of individuals of a species caught divided by the total number of individuals caught:

$$\text{Shannon Index of Diversity: } H' = -\sum p_i(ln p_i)$$ (3)

The average upstream and downstream dissolved oxygen, temperature, turbidity, discharge, and fish diversity was calculated. The measurements made at the above and below sites were not included in the average upstream and downstream measurements. The above and below sites were used to analyze the difference caused by one section of the falls. Sampling sites above and below were excluded from the average upstream and downstream calculations because the above sampling location was located between the upper portion falls and the main falls and could show some impact of the upper falls, therefore, skewing the upstream data. A two-tailed $t$-test was then used with a $p$-value criteria of 0.05 in order to determine if there was a significant difference between the average values upstream and downstream from the waterfall. A two-tailed $t$-test was also used to determine if there was a significant difference between directly above and below the waterfall. Two multiple regression analyses were also used to model the relationship between the various measured characteristics and fish diversity. One of the multiple regressions used species richness, or the total number of species caught, as the dependent variable and the other regression used the Shannon Diversity Index as the dependent variable. Both regressions used dissolved oxygen, temperature, turbidity, and velocity as the independent variables.
Results:

Statistically significant differences between upstream and downstream conditions were found for three out of the four different habitat characteristics that were investigated during this study. No significant differences were found between habitat conditions at the sampling locations directly above and below the waterfall. In general, the values for the above and below sampling points were relatively similar to the downstream average for each of the characteristics that were measured.

1. Fish Diversity:

A total of 39 fish were caught over the 13 week sampling period. A total of 12 species were caught, with ten species being caught upstream from the waterfall, while only four species were caught below the falls. A much greater number of individuals were also caught upstream than downstream. Table 1 shows the total number of each species caught upstream and downstream from the waterfall. All of the upstream sites had a species richness of 5 species, which was higher than the downstream sites, which had 0 species at Downstream 1, 3 species at Downstream 2, and 1 species at Downstream 3. Upstream 2 had the highest Shannon Diversity Index of 1.523, while both Downstream 1 and Downstream 3 had the lowest index of 0.000. Upstream had a higher average Shannon Diversity Index than downstream at a nearly significant level (p=0.062) (Figure 5). The downstream sites also had a much higher standard deviation than the upstream sites. Additional species were observed jumping out of the water.
downstream from the falls but were not included in the calculations because they were not caught in the minnow traps.

![Average Shannon Diversity Index](image)

**Figure 5: Average Shannon Diversity Index for fish caught upstream and downstream from the waterfall**

2. **Dissolved Oxygen:**

Dissolved oxygen was found to be significantly greater downstream from the falls than upstream ($p=3.20 \times 10^{-27}$). The average upstream (Sites Upstream 1, Upstream 2, and Upstream 3) dissolved oxygen level was 6.77 mg/L while the average downstream (Sites Downstream 1, Downstream 2, and Downstream 3) dissolved oxygen level was 8.18 mg/L. Upstream dissolved oxygen levels had greater variation than the downstream dissolved oxygen levels. Dissolved oxygen levels upstream also fluctuated over a wider range (2.37 mg/L) than downstream levels (1.02 mg/L). Downstream 3, the furthest downstream site, had the highest average dissolved oxygen level of 8.24 mg/L, while Upstream 3, the furthest upstream site, had the lowest
average dissolved oxygen level of 6.65 mg/L (Figure 6). Dissolved oxygen levels were not significantly different at the sampling locations directly above and below the falls locations (p=0.88). The average dissolved oxygen level at both of those sampling locations was 8.08 mg/L and had a standard deviation of approximately 0.28 mg/L (Figure 6).

![Average Dissolved Oxygen Concentration](image)

**Figure 6:** Average dissolved oxygen levels at each site over the 13 week sampling period

### 3. Temperature:

Water temperature was not statistically different between the upstream and downstream locations (p=0.254). The average upstream temperature was 23.7°C, which was lower than the average downstream temperature of 24.1°C. The water temperature upstream from the falls ranged from 20.5°C to 27.1°C, while downstream water temperatures ranged from 21.2°C to 26.9°C. Sites Downstream 2 and 3 had the highest average temperature (24.1°C) while Upstream 2 had the lowest average temperature (23.5°C) (Figure 7). All sampling sites had approximately the same amount of variance. The difference between the average water
temperature at the above and below sampling locations was not statistically significant 
(p=0.746). The average temperature directly below the falls was lower than directly above the 
waterfall (Figure 7), which was opposite of the upstream and downstream trend. The difference 
in temperature between directly above and below the waterfall (0.1 °C) was less than the 
difference in temperature between upstream and downstream from the waterfall (0.4 °C).

![Average Water Temperature](image)

**Figure 7: Average water temperature at each site over the 13 week sampling period**

4. **Turbidity:**

Water clarity measurements were significantly higher (indicating a lower turbidity) 
upstream from the waterfall than downstream (p=0.001) (Figure 8). The standard deviation of 
the sampling locations was fairly high but relatively similar across the sites. The water clarity 
values for directly above and below the falls followed a similar trend as the upstream versus 
downstream trend, however, there was not a significant difference found (p=0.745) (Figure 8).
5. Velocity and Discharge:

The average velocity downstream from the waterfall was more than twice as fast as the average velocity upstream (Figure 9a). This represents a statistically significant difference between the upstream and downstream velocity (p=8.567x10^{-11}). There was not a significant difference between the upstream and downstream discharge (p=0.824). The average downstream discharge was slightly lower than the average upstream discharge (Figure 9b). The discharge at both Upstream 1 and Downstream 1 had a standard deviation of around $9.5 \text{ m}^3/\text{s}$. Most of this variation comes from an abnormally high estimated discharge on June 23, 2018, following a heavy rain. Both the upstream and downstream discharge on that day were approximately $42 \text{ m}^3/\text{s}$ which was much higher than the average discharge of around $15 \text{ m}^3/\text{s}$.
Figure 9: (a) Average velocity and (b) average discharge at Upstream 1 and Downstream 1 over the 13 week sampling period (includes estimated data)

6. Regression Analysis:

Both of the regression analyses that were performed did not have significant p-values for any of the independent variables. In both cases, velocity was the independent variable that came closest to a significant value, with a p-value of 0.11 in the species richness regression, and a p-value of 0.21 in the Shannon Diversity Index regression. Both regressions also had relatively similar and low adjusted $R^2$ values, however, the data fit the species richness regression slightly better. The adjusted $R^2$ value for the species richness regression (5) was 0.14, while the adjusted $R^2$ value for the Shannon Diversity Index regression (4) was 0.11. The equations for the two regression models are shown below:

\[
\text{Shannon Diversity Index} = -0.7867(V) - 0.0198(Turb.) - 0.0214(Temp.) - 0.0923(DO) + 2.1852 \tag{4}
\]

\[
\text{Species Richness} = -3.0109(V) - 0.0602(Turb.) - 0.0003(Temp.) - 0.1779(DO) + 4.7465 \tag{5}
\]
Discussion:

The data clearly show that there is a significant difference in habitat conditions upstream and downstream from Falls Park. Significant differences between upstream and downstream levels were found for all of the variables that were examined in the study, except the fish diversity and temperature. However, not all of the variables differed as hypothesized. As hypothesized, dissolved oxygen was higher downstream from the falls and the turbidity was also higher downstream from the falls, indicating less clear water. Temperature was found to be higher downstream from the falls as well, but not at a statistically significant level. The velocity, however, actually showed a different trend than hypothesized. Velocity was found to be significantly higher downstream from the falls when compared to upstream. Fish diversity also differed from the expected results. A greater diversity in the fish communities was found upstream from the waterfall than downstream. Although this was not a significant difference at the p=0.05 significance level, it was nearly significant and would be significant at the p=0.10 significance level. It is likely that there would be a significant difference at the p=0.05 level with a larger sample size.

There are several possible explanations for why the measured diversity of fish did not follow the expected trend. One factor that likely had a big impact on the calculated fish diversity was the change in sampling method from seining to minnow traps that had to occur due to the flooding that prevented wading in the river for the first portion of the summer. This means that many of the larger species of fish, those that were larger than 1 inch in diameter, could not fit into the minnow traps and were therefore excluded from the study. Some of these larger species were observed jumping from the water while sampling, especially at the
downstream sampling locations. This indicates that there was likely a higher diversity of fish than what was actually measured.

Another possible reason for the lack of smaller species below the falls could be the higher velocity measured downstream from the falls. It is possible that smaller fish are unable to fight the current to live directly downstream from the waterfall and would be found again further downstream than the sampling sites that were selected. The data do slightly support this idea in that no fish were caught at the downstream site closest to the falls (Downstream 1) where the velocity appeared to be highest. The results of the multiple regression analysis also partially support this idea. Although the p-value for velocity was not at a significant level, it was low enough to potentially be significant if a larger sampling size could have been obtained. The impact of velocity on the size and diversity of fish species in an area could be an interesting topic for future study.

Finally, the lower than expected number of fish caught below the falls could also possibly be explained by other factors of water quality that were not measured during this study. In particular, the wastewater outlet for the Smithfield Foods meat packing facility in Sioux Falls empties into the Big Sioux River just downstream of Falls Park between the falls and the spillway of the diversion channel. Although the exact location of the outlet was not identified during the study, this was the same area that the downstream sampling took place. In fact, during the time that sampling was occurring, a malfunction in the Smithfield Foods wastewater treatment plant caused almost 2,200 pounds of ammonia to be released on August 18, 2018 (Pfankuch 2018; KELO News). This level is much higher than the 102 pounds daily limit of ammonia that Smithfield is permitted to release into the Big Sioux River by the South Dakota
Department of Environment and Natural Resources (SD DENR) under the Surface Water Discharge permitting program. In total, the plant released more ammonia in a four day period than would be permitted over a four-month period (Pfankuch 2018). The SD DENR reported that there was no risk to human health, but fish were potentially at risk due to the release. Although this particular incident likely did not impact the results of this study since it occurred near the end of the sampling period, Smithfield has previously been fined for violating their discharge permit (Pfankuch 2018) which could contribute to the lower fish diversity that was found downstream from the falls.

Dissolved oxygen followed the expected trend of being higher downstream than upstream from the waterfall. However, despite the higher levels of dissolved oxygen downstream, the concentrations of dissolved oxygen at the sampling locations directly above and below the falls were not significantly different from each other and were also approximately the same concentration as the downstream average dissolved oxygen concentration. This is likely because the concentration of oxygen dissolved in the water is dependent on temperature (Risberg 2009). As the water went over the upper falls, it likely became saturated, or possibly supersaturated, with dissolved oxygen preventing any more oxygen exchange with the atmosphere. As the water continued to fall over the middle and lower falls, no more oxygen could be added to the water because it was already holding the maximum amount of dissolved oxygen possible at that temperature.

Turbidity followed the expected trend with the water downstream of the waterfall being more turbid than upstream. This is likely because the water erodes the rock and stirs up sediment at the base of the waterfall suspending it in the water column and carrying it
downstream. As more rock erodes and gets picked up by the water, the water becomes less clear resulting in the lower water clarity measurements that were recorded downstream from the waterfall.

Velocity was found to be significantly higher downstream from the waterfall, which was opposite of what was predicted. The most likely reason for this is because the channel becomes relatively narrow and shallow downstream from the waterfall, which because the discharge should stay approximately the same and the width and average depth decreased, it means the velocity must increase. The data do show a slight difference in the discharge upstream and downstream from the waterfall, however, it was not statistically significant and was likely due to sampling error than an actual difference in discharge. At the downstream transect, the deepest and fastest flowing part of the river was located between points along the transect, making it so the estimated discharge reported is likely a slight underestimate. A better estimate of discharge at both the upstream and downstream locations could have been made using a greater number of sampling points along the transect. As mentioned previously, velocity seemed to have the biggest impact on where smaller fish were found according to the multiple regression models produced in this study.

**Future Work:**

The biggest limitation of this study came from the omission of larger fish species by using minnow traps instead of the seines that were originally planned. Future work on this topic should attempt to use methods that would be able to capture all of the different sizes of fish present in the river, such as seines, trap nets, or hoop nets. If this study were repeated in a non-
flood year, it would also be beneficial to measure discharge and velocity for the entire sampling period, instead of estimating data from a stream gage station, which may have introduced some error into this study. If there were no time limitations on this study, a larger sample size would also be beneficial in order to better determine statistical differences between upstream and downstream fish diversity. Finally, if a future study were to be done in this same area, it would be beneficial to include other water quality measurements such as ammonia and nitrates in order to determine if the presence of the Smithfield Foods processing plant near the downstream sampling locations had an impact on the low fish diversity found in that area.

**Implications of Study:**

While this study clearly showed that waterfalls impact on the habitat conditions present in a river, the implications related to fish diversity are less clear due to the relatively small sample size and omission of larger fish from the study. Despite the limitations, the difference in upstream vs downstream fish diversity is important to consider when making river conservation and/or restoration decisions in Sioux Falls. While the study did not support the hypothesis that higher fish diversity would be found downstream from the waterfall, it did show that there was a nearly significant difference between upstream and downstream diversity levels, indicating that the presence of waterfalls should be considered when making decisions about river conservation. In Sioux Falls, this study appears to show that conservation efforts should focus on the area upstream of Falls Park where the higher fish diversity was found. In addition, this study could also present the idea that restoration and clean-up efforts should be focused on the areas downstream of the waterfall because of the relatively low fish diversity there.
While the conclusions on fish diversity made in this study cannot likely be applied to all waterfall systems due to the urban nature of the falls on Big Sioux River, it is likely that the general conclusions made about the impact of the waterfall on habitat conditions could be applied to other waterfalls as well. In addition, understanding the processes by which waterfalls impact river conditions could provide some interesting ideas for potential biomimicry in certain human systems. For example, understanding the process of how waterfalls increase the dissolved oxygen level of a river could allow for waterfall-like structures to be added to water treatment processes that require higher levels of dissolved oxygen levels.

**Conclusion:**

This study clearly supports the idea that waterfalls have a significant impact on river characteristics and create different microhabitats in terms of dissolved oxygen, turbidity, and stream velocity when comparing upstream and downstream locations. While the data did not support the idea that downstream fish diversity was greater than upstream diversity, it did indicate that fish diversity upstream from the waterfall was greater at a nearly significant level. With more sampling time and therefore, a greater sample size, the data would likely show a significantly higher fish diversity upstream from the waterfall than downstream.

It is important to consider that this study only measured the diversity of relatively small fish, therefore it is possible that the initial hypothesis of greater fish diversity downstream could be supported if all of the fish community could have been sampled as originally planned. It would be beneficial for a follow up study to further examine the fish diversity upstream and downstream from the falls using different fish capture methods such as seining, which was
originally planned for this study, or larger trap and hoop nets that could catch all of the different sizes of fish in the river.

While this study may not completely show that waterfalls have an impact on total fish diversity, waterfalls certainly have an impact on the aquatic habitat conditions downstream from the falls. In this particular case, dissolved oxygen, turbidity, and stream velocity were all found to be higher downstream from the waterfall. Neither temperature nor fish diversity had a significant difference between upstream and downstream levels, however, fish diversity was nearly significant, with a greater fish diversity being found upstream from the waterfall. While this study may have limitations in the analysis of overall fish distribution due to larger species being excluded, it clearly shows that waterfalls can create unique microhabitat conditions in a river ecosystem.
References:


University of Wisconsin Extension. 2006. Transparency: a water clarity measure. UW Extension, WI.

