# *A Temporal Assessment of Channel Morphology Downstream from the Tuttle Creek Dam*

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Research Report

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# Table of Contents

**Acknowledgments** ........................................................................................2

**Abstract** ........................................................................................3

**1. Introduction** ........................................................................................3

1.1. Downstream Incision Rates ........................................................................5

1.2. Changes in Peak Discharge ........................................................................7

1.3. Channel Morphology ........................................................................8

1.4. Research Objectives ........................................................................10

**2. Study Area** ........................................................................................11

**3. Methods** ........................................................................................12

3.1. Objective 1: Change in Downstream Flow Regime ..........................................12

3.2 Objective 2: Change in Downstream Bed Stability ..........................................13

3.3 Objective 3: Assessment of Downstream, Long-Term Degradation Lines ...........15

**4. Results and Discussion** ........................................................................................19

4.1. Objective 1: Change in Downstream Flow Regime ..........................................16

4.2 Objective 2: Change in Downstream Bed Stability ..........................................18

4.3 Objective 3: Assessment of Downstream, Long-Term Degradation Lines ...........21

**6. Channel Evolution** ........................................................................................25

**7. Conclusion** ........................................................................................28

**8. References** ........................................................................................30

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# Abstract

Dams play a significant role in protecting the health and safety of downstream communities. However, dams also cause unintended changes to the natural environment. The impact of dams and other disturbances on channel morphology can be determined using channel evolution models. This research will try to investigate the complex natural processes of the Big Blue River that are impacted by the upstream Tuttle Creek Dam and reservoir. To do this, three major research objectives were assessed. First, using USGS recorded stream data, a temporal assessment was made to examine the changes the Tuttle Creek Dam has caused. A change in the downstream flow regime has been observed within the study area for several hydrologic parameters. Second, a segmented linear regression analysis was created using USGS stream gage height and discharge data to assess the downstream bed stability over time. Channel bed degradation has occurred, but it appears to have stabilized in the past 25 years. Third, by comparing observations to historical degradation lines data collected by the USACE, it was possible to quantify the changes in cross-sectional areas between years and determine what channel evolution model was present in the Big Blue River. As channel degradation occurred, the cross-sectional area consistently increased in each range. The Simon and Hupp channel evolution model was found to have best corresponded to this river.

## 1. Introduction

Reservoirs are highly sought out places for people to do recreation in the summertime, especially in the state of Kansas. People use these resources for swimming, boating, water skiing, fishing, tubing, camping, etc. Even in the winter, people use these resources to do ice fishing, ice skating, and pick-up hockey games. When places such as Kansas do not have mountains or the ocean, the residents rely on reservoirs to fulfill their recreation needs, creating a healthier society because people are out and active.

With artificial reservoir development, a region's tourist attractiveness enhances, and tourism around the reservoirs develops. Most reservoirs have been created as a result of constructing a dam. The history of dams goes as far back as 2900 B.C.E on the Nile, and several others were created in Egypt, Syria, Mesopotamia, Rome, Persia, Babylon, Greece, and Anatolia (Duda-Gromada, 2012). The goals of building dams and creating reservoirs have varied over time. It started off as irrigation and water supply, then went to navigation, flood protection, and alternative energy sources (Duda-Gromada, 2012). Nowadays, tourism and recreation are big drivers to the community's surrounding reservoirs, but with these positive things, some ramifications come with them.

For example, reservoir sedimentation occurs when sediments accrue inside reservoirs and lakes (McCartney et al., 2001). Dammed reservoirs and lakes inherently interrupt the natural continuity of sediment transport, creating even more importance for infrastructure that allows sediment transport to continue further downstream. Over time the accumulation of sediment in reservoirs and lakes causes the total reservoir capacity, the operating life of the dam, and flood control effectiveness to decrease (Kondolf et al., 2014). Furthermore, Kondolf et al. found more evidence of hungry water, which happens when water erodes away a channel and ecosystems downstream of a dam are starved of sediment.

Example case studies of reservoir sedimentation in Kansas include Kanopolis and Tuttle Creek dams. Between 2008 and 2010, 98% of the sediment that flowed from upstream of these dams was trapped in the reservoirs by the dams themselves (Juracek, 2011). This is an exceptional number and illustrates the drastic effect that dams can have on their local environment. Sediment entrapment remains an important consideration for dam construction and the continued maintenance of dams. The federal government has been continually interested in the sedimentation of the Tuttle Creek Reservoir in Kansas since at least 1972 (Juracek, 2011).

Sediment transported into the reservoir will become trapped due to the design of most large dams (Palmieri et al., 2001). The International Commission on Large Dams (ICOLD) defines a large dam as "a dam with a height of 15 meters or greater from lowest foundation to crest or a dam between 5 meters and 15 meters impounding more than 3 million cubic meters" (ICOLD, n.d.). As of 2001, there were approximately 45,000 large dams in the world, most of which were built after 1950 (Palmieri et al., 2001).

In addition to reservoir sedimentation, dams have a wide range of environmental impacts that affect the hydrology, geomorphology, and ecosystems of the rivers that they are located on (McCartney et al., 2001). The following sections focus on the environmental impacts on alluvial rivers downstream of dams.

### 1.1. Downstream Incision Rates

Increased incision rates are one of the largest problems with dams and have created problems for almost every reservoir where dams are located (McCartney et al., 2001). Following a dam's construction, downstream incision rates have been shown to increase in most cases (Williams and Wolman, 1984). This mechanism works via sediment entrapment. Sediment entrapment catches sediment preventing it from flowing downstream (and thus results in reservoir sedimentation). Sediment entrapment prevents the riverbed from recharging sediment, as only water flows through this channel section. Essentially the river will deposit some transported sediment to the newly eroded scour (Williams and Wolman, 1984). However, without this deposited sediment, the stream will erode away material without refilling it from upstream. This will lead to a higher rate of incisions compared to the natural rate on the beds of the streams.

One example looked at research conducted on the Oconee River in Georgia. A dam was constructed on the river in the 1950s, and from then until roughly 1995, the river downstream of the dam saw an increased vertical incision of roughly 1 meter with lateral erosion at roughly 2-5% per year (Ligon et al., 1995). This incision rate decreases as you go further downstream as sediment becomes available again for the beds to recharge (Williams and Wolman, 1984). Figure 1 looks at the Kanopolis Dam and reservoir on the Smoky Hill River in Kansas. The researchers saw a dramatically increased incision rate following the dam's construction (Williams and Wolman, 1984).

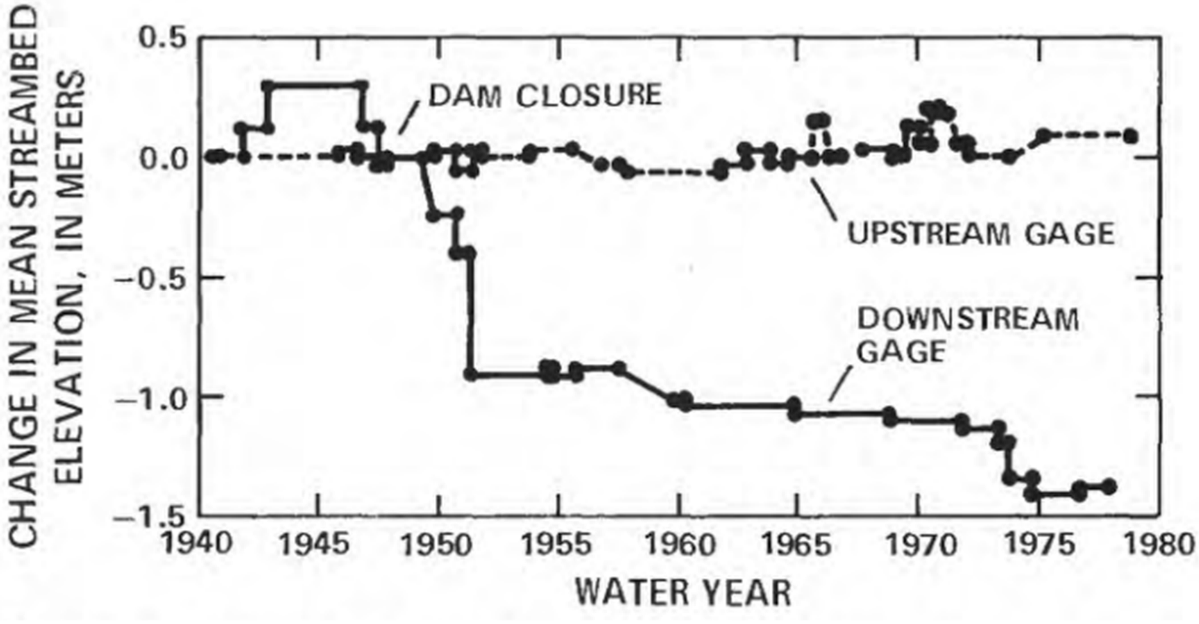

**Figure 1**. The changes in mean bed elevation on the Smoky Hill River in Kansas. Looking at gages from upstream and downstream of the dam, researchers were able to compare the relative rates of channel bed incision. Note how following the dam's construction (i.e., Dam Closure), the downstream change in elevation plummeted. Figure retrieved from page 17 of Williams & Wolman (1984).

### 1.2. Changes in Peak Discharge

Many dams work by capturing intense flooding events and releasing them slowly over a longer period, thereby reducing the flashiest of flooding events (Graf, 2006) and, thus, the flow regime. Statistical analysis of 36 dams across the United States saw a reduction in the maximum instantaneous flows (i.e., flooding) by 67%, and peak flows were reduced by 71% for 1-day extremes (Graf, 2006). This stops large flooding events and reduces their overall severity, as seen in Table 1.

**Table 1**. The relative reduction in some hydrologic parameters with instantaneous and 1-day maximum shows the largest reduction in magnitude in controlled rivers. Minimum flows also show a relative increase in discharge. The number of high pulses did not see a large change; however, the duration of high pulses experienced a large change. Table retrieved from page 350 of Graf (2006).

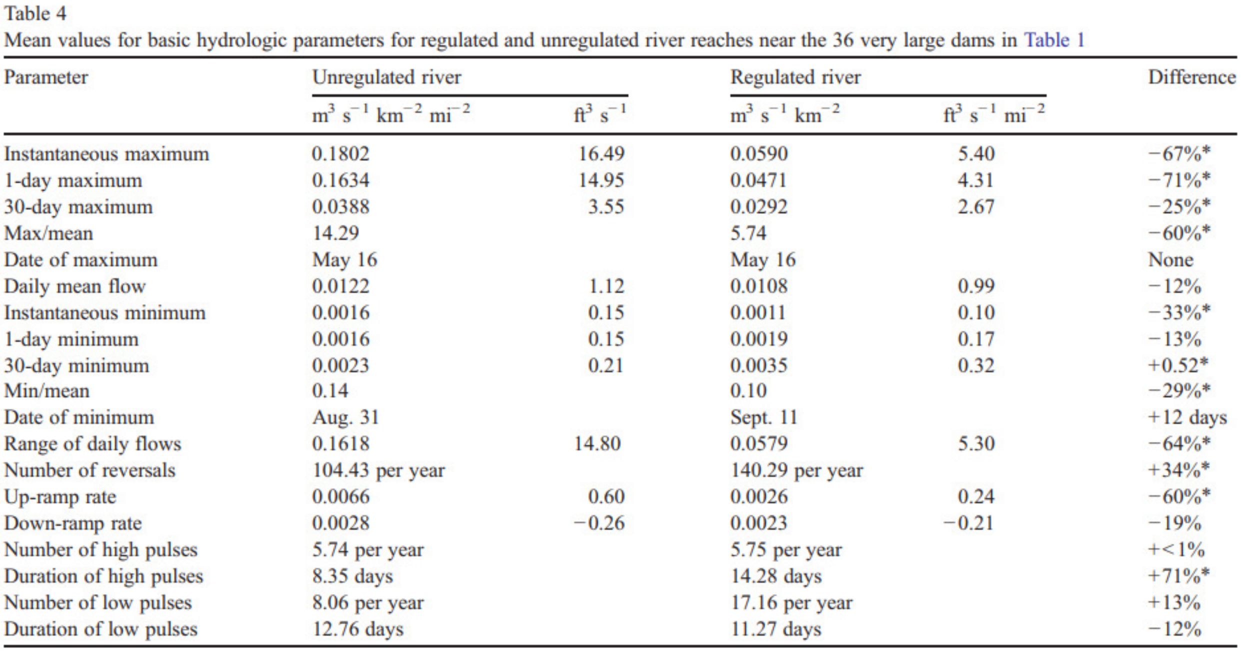

Table 4
Mean values for basic hydrologic parameters for regulated and unregulated river reaches near the 36 very large dams in Table 1

| Parameter | Unregulated river | | Regulated river | | Difference |
|---|---|---|---|---|---|
| | $m^3\ s^{-1}\ km^{-2}\ mi^{-2}$ | $ft^3\ s^{-1}$ | $m^3\ s^{-1}\ km^{-2}$ | $ft^3\ s^{-1}\ mi^{-2}$ | |
| Instantaneous maximum | 0.1802 | 16.49 | 0.0590 | 5.40 | −67%* |
| 1-day maximum | 0.1634 | 14.95 | 0.0471 | 4.31 | −71%* |
| 30-day maximum | 0.0388 | 3.55 | 0.0292 | 2.67 | −25%* |
| Max/mean | 14.29 | | 5.74 | | −60%* |
| Date of maximum | May 16 | | May 16 | | None |
| Daily mean flow | 0.0122 | 1.12 | 0.0108 | 0.99 | −12% |
| Instantaneous minimum | 0.0016 | 0.15 | 0.0011 | 0.10 | −33%* |
| 1-day minimum | 0.0016 | 0.15 | 0.0019 | 0.17 | −13% |
| 30-day minimum | 0.0023 | 0.21 | 0.0035 | 0.32 | +0.52* |
| Min/mean | 0.14 | | 0.10 | | −29%* |
| Date of minimum | Aug. 31 | | Sept. 11 | | +12 days |
| Range of daily flows | 0.1618 | 14.80 | 0.0579 | 5.30 | −64%* |
| Number of reversals | 104.43 per year | | 140.29 per year | | +34%* |
| Up-ramp rate | 0.0066 | 0.60 | 0.0026 | 0.24 | −60%* |
| Down-ramp rate | 0.0028 | −0.26 | 0.0023 | −0.21 | −19% |
| Number of high pulses | 5.74 per year | | 5.75 per year | | +<1% |
| Duration of high pulses | 8.35 days | | 14.28 days | | +71%* |
| Number of low pulses | 8.06 per year | | 17.16 per year | | +13% |
| Duration of low pulses | 12.76 days | | 11.27 days | | −12% |

Reduction in mean annual floods shows dams greatly impact the flow regime of rivers and watersheds in the United States (FitzHugh & Vogel, 2011). The Central Plains region of the United States saw an 18% reduction in median annual floods on small and medium streams and a 30% reduction in median annual floods on large rivers. Essentially dams reduced mean annual floods in almost all rivers that dams were found in (FitzHugh & Vogel, 2011). Figure 2 displays this relative reduction of mean annual floods from dams in many major watersheds across the United States.

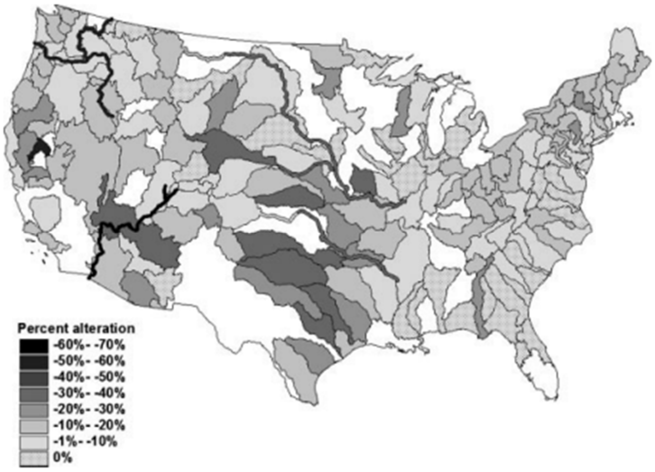

**Figure 2**. Illustration of the reduction in mean annual floods in the United States on major watersheds. Figure retrieved from page 6 of Fitzhugh & Vogel (2011).

## 1.3. Channel Morphology

Rivers and streams naturally erode the material along their banks and channel beds (Williams and Wolman, 1984). This is done through several different mechanisms that work to erode away the banks and beds of rivers. One primary mechanism is abrasion caused by the shear stress of the water itself. The weight of the water will push down on the river bed and make it more likely to move grains of sediment, resulting in erosion (Westgate, 1907). Once eroded, sediment will begin to work its way downstream via different transport mechanisms such as saltation, traction, or suspension. This sediment will continue downstream until it reaches the final outlet, usually the ocean. However, in the case of a dam, the sediment will usually be prevented from continuing downstream (Juracek, 2011).

As was seen with sediment entrapment, downstream incision, and changes in peak discharge, these components can drastically alter the channel morphology of the river where the dam is located (Pizzuto, 2002). The largest contributor to the change in channel geomorphology is the reduction in peak discharge. As seen in Table 1, a reduction in 30-day maximum discharge reduces the movement of larger sediment particle sizes (Graf, 2006). This has the effect of stabilizing a river and reducing its chances of channelization. In the same paper, the erosion of streambanks, channel bars, and channel islands was 60% less than in unregulated rivers (Graf, 2006). The active floodplain was also seen to decrease by 72% on regulated reaches, and rivers were found to be 32% less complex than unregulated rivers (Graf, 2006).

Channels will enter into a new equilibrium following the installation of a new dam (Pizzuto, 2002). This can also create new mean discharge rates and mean sediment load rates. Sediment can change from larger-sized sediment to fine-grained, meaning the sediment profile changes (Pizzuto, 2002). Streams are also less likely to channelize due to the reduction in peak discharge (Friedman et al., 1998). This reduction in larger discharge events can reduce the complexity of the river in braided systems. Braided channels will likely narrow downstream from a dam (Friedman et al., 1998). Among 35 streams studied in one paper, 11 saw channel narrowing, and 13 saw a reduced channel migration rate. One case with both channel narrowing and reduced channel migration rate. There were nine cases where channel narrowing did not occur; however, there was insufficient information to determine the channel migration rate. One last case where both channel narrowing and channel migration did not happen. (Friedman et al., 1998). These geomorphic parameters are better illustrated in Figure 3.

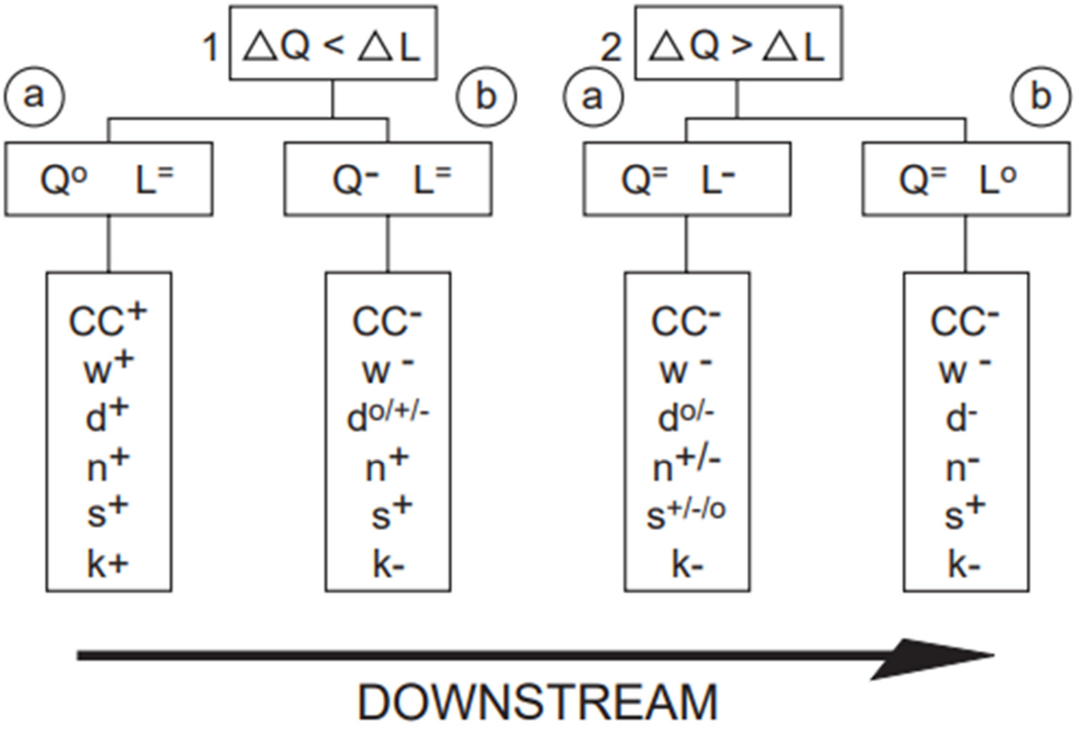

**Figure 3.** Four scenarios of hydrologic components that can change going downstream of a dam, with different starting river components being greater discharge or greater sediment load. ΔQ is the change in discharge, and ΔL is the change in sediment load. CC is channel capacity, w is width, d is depth, n is roughness, s is the slope, and k is conveyance. 0 represents no change, + represents increasing change, - represents decreasing change. 1a and 2b are examples of extremes. Note how discharge is reduced immediately downstream of a dam in part 1b. This decreases channel capacity and width but increases roughness and slope. In 2a, sediment load decreases, decreasing channel capacity, width, and depth depending on the stream. Figure 3 retrieved from page 31 of Petts & Gurnell (2005).

## 1.4. Research Objectives

The goal of this report is to study the evolution of a river following the installation of a Tuttle Creek Dam on the Big Blue River near Manhattan, Kansas. This report will examine some of these impacts as they relate to the downstream channel morphology, hydrologic parameters for rivers, and some ecological effects that dams can cause. To assess channel morphology, three research objectives are examined in this report:

- Assess the change in the flow regime following upstream dam installation using USGS recorded flow data.
- Assess the downstream bed stability over time using USGS gage height information.
- Compare observations to historical degradation line data collected by the USACE.

By exploring the objectives in this report, an examination can be made of how dams affect the natural processes within the rivers and watersheds they are located in.

## 2. Study Area

The study area includes the Tuttle Creek Dam and reservoir located in eastern Kansas, along with an approximately 9-mile section of the Big Blue River immediately downstream from the dam. The Big Blue River provides up to 50% of the water for the Kansas River (Kansas Water Office, 2017). The Tuttle Creek reservoir watershed encompasses approximately 15495 kilometers of drainage area. About 81 cm of precipitation falls within the watershed, primarily between April and September, and the primary soil type within the watershed is silty clay loams (Kansas Water Office, 2017). Figure 1 outlines the Tuttle Creek reservoir and the drainage area for the Big Blue River.

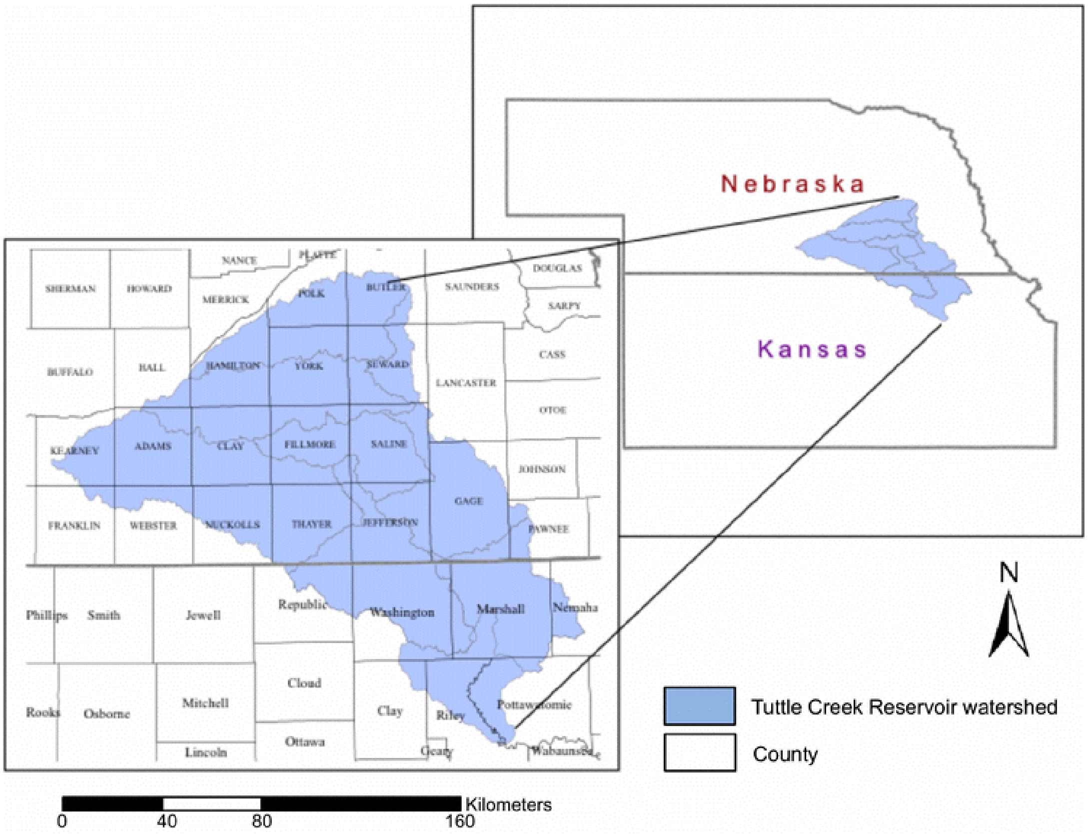

**Figure 4**. The drainage area of the Big Blue River. Figure retrieved from Rhodes et al. (2018)

# 3. Methods

## 3.1. Objective 1: Change in Downstream Flow Regime

Data was acquired from the Manhattan Big Blue River USGS gage (06887000) located approximately 9 miles downstream from the Tuttle Creek Reservoir to assess the change in hydrology following the Tuttle Creek dam installation. Data for this stream gage has been reliably measured from 1951 until today (USGS, n.d.). The Indicators of Hydrologic Alteration (IHA) software was used to assess flow data. IHA software was developed to evaluate hydrologic changes following a large alteration to a natural river system (Nature Conservancy, n.d.). The closure of the Big Blue River occurred on July 4, 1959 (USACE, n.d.). Therefore, this date was chosen to mark the pre and post-time period for the analysis. A table was generated from the IHA software to assess some major hydrologic components—Table 2 shows which hydrologic parameters were assessed. Data generated in the IHA software was then used within RStudio using the Mann-Whitney U test and the Kolmogorov-Smirnov test to determine the statistical significance of the hydrologic components. These tests were chosen for their ability to test for normality with non-parametric data (Statistical Methods, 2019). Data was tested against a 95th percent confidence level for statistical significance.

**Table 2**. Hydrologic parameters assessed in the IHA, PeakFQ, and RStudio software. Table retrieved from pg. 42 of Bigham, K. (2022).

| Statistic | Magnitude | Duration | Frequency | Timing |
|---|---|---|---|---|
| **Daily Flow** | -Median daily discharge (cms) | -Median high flow duration (days)<br>-Flow duration curves | -Median high flow counts (#/yr)<br>-Flow duration curves | -Median rising and falling limb rates (cms/day)<br>-Median date of peak discharge |
| **Annual Peak Flow** | -Median annual peak discharge (cms)<br>-Flood frequency analysis | N/A | -Flood frequency analysis | N/A |

The last software used was the PeakFQ software developed by the USGS to generate the flood-frequency analysis of streamflow records (USGS, 2014). A regional skew of -0.2 was used as recommended by the USGS for the Manhattan area of Kansas (USGS, 1982). This was used to reference flood flows and to confirm the flow duration curves generated by the IHA software.

### 3.2 Objective 2: Change in Downstream Bed Stability

To assess the downstream bed stability over time of the Big Blue, the downstream bed stability graph created by Juracek (2011) for the years 1953-2009 was extended to 2022. To do this, data collected from the same USGS gage stated in objective one was utilized to find the reference stage from 2007-2022 using 70.79 (cubic meters per second) as the standard stream flow, based on Juracek's (2011) methodology.

Gages measure and record a stream's water level (gage height or reference stage). Stream flow, also called discharge, is computed from measured water levels using a site-specific relation, called a stage-discharge rating curve, developed from onsite water level and streamflow measurements (U.S. Department of the Interior, 2018). By computing the gage height that relates to discharge for each rating curve developed during the period of record of a gaging station, trends in the elevation of the channel bed can be inferred by plotting the subsequent time-series data (Juracek, 2011). It may be inferred that the channel-bed elevation has lowered over time due to erosion if the stage for the reference discharge has a downward (negative) trend (Juracek, 2011). Conversely, it may be inferred that the channel-bed elevation has risen over time due to aggradation if the stage for the reference discharge has an upward (positive) trend (Juracek, 2011). No trend indicates that the channel bed has been essentially stable (Juracek, 2011).

To extend Juracek's (2011) graph dates from 2007 to 2022, where the measured daily discharge was 70.79 cms, were found. The gage height related to the discharge for that day and the date were recorded. The dates were then converted into decimal year. To do this, a Julian calendar was used to find the exact day of the year, and then this number was divided by 365, or 366 if it was a leap year, to get the decimal point and added to the year of the event (e.g., 2007.80 = October 18, 2007). To further assess the reference discharge-gage height data, segmented linear regression models were generated with RStudio code from https://rpubs.com/MarkusLoew/12164, and breakpoints were estimated for the streambed. Segmented slopes of the long-term degradation were also calculated.

### 3.3 Objective 3: Assessment of Downstream, Long-Term Degradation Lines

Using data collected from USACE, the historical degradation lines of the Big Blue River were determined at nine points or ranges (Figure 5), which were taken downstream of Kanopolis Dam (D. Wansing, USACE, personal communication, July 1, 2022). Then, using Google Earth Pro, data files corresponding to each range were processed to create a map of the degradation lines.

**Figure 5**. Mapping of degradation ranges from A to I along the Big Blue River.

Degradation range surveys were conducted in seven different years, and these were 1961, 1972, 1995, 2005, 2010, 2015, and 2021. Ranges A through C were surveyed in all seven years. Range D was only surveyed six times, with no survey occurring in 2021. Range E was surveyed four times, with no survey occurring in 2005, 2010, or 2021. Range F was surveyed six times, with no survey occurring in 2005. Range G was surveyed six times, with no survey occurring in 2010. Range H and Range I were only surveyed three times, with no survey occurring past 1995.

Surveys in 2021 and 2015 were conducted using USACE's RTK base station. Surveys prior to 2015 were conducted using monumentation, created during the construction of Tuttle

Creek Lake. According to (D. Wansing, USACE, personal communication, July 1, 2022), "These monumentation were brass or aluminum stamped caps that were set in concrete or attached to steel rods roughly 18" in length. Steel rods were chosen to make it easier to locate the monuments using a magnetic locator and signs around the monuments to prevent tampering and make it easier to find them. In addition, these monuments were spaced on each side of the channel to depict degradation or erosion of the channel for monitoring releases at various locations."

Monumentation surveying can occur in two methods. In the method used in the older ranges, the surveyors would use a level/total station and survey the cross-section between the monuments. This was achieved using the originally established elevation (NGVD29). The current method of monumentation was established by the USACE survey crews. Each crew completed their surveys using RTK and updated their elevations to NAVD88. These lines were derived from the measurements of the distance and the elevation of the banks. Cross-sectional areas were taken for each range in order to provide a more coherent understanding of the current state of each range. Once plotted, cross-sectional areas were taken for each range to provide a more coherent understanding of the current state of each range line.

## 4. Results and Discussion

### 4.1 Objective 1: Change in Downstream Flow Regime

Statistical analysis of the Big Blue River following the installation of the Tuttle Creek dam has shown significant changes in several hydrological characteristics. These changes are summarized in Table 3. Statistically significant results were found for the median rise and fall rates for pre- and post-time periods. Statistically significant results for median high pulse duration and median annual peak discharge for the post-time period and median date of annual peak flow for the pre-time period. Large changes in the hydrologic parameters were observed for the pre-and post-time periods indicating that the Tuttle Creek dam played a significant role in altering the Big Blue River.

**Table 3**. Comparison of hydrologic parameters for the Big Blue River near Manhattan, Kansas, during the pre and post-dam time periods. **Bold*** indicates statistically significant results with a confidence level at or exceeding 95%.

| **Flow Parameter** | **Pre-Dam (1951 -1959)** | **Post-Dam (1960 - 2022)** |
|---|---|---|
| Median Daily Discharge (cms) | 19.1 | 25.5 |
| 1% Exceedance Probability (cms)<br>99% Exceedance Probability (cms) | 3032<br>250.2 | 1332<br>179.9 |
| Median High Pulse Count (#/yr)<br>Median High Pulse Duration (days/yr) | 7<br>5.5 | **8***<br>**11*** |
| Median Hydrograph Rise Rate (cms/day)<br>Median Hydrograph Fall Rate (cms/day) | **1.42***<br>**-1.84*** | **1.13***<br>**-0.57*** |
| Median Date of Annual Peak Flow | **6-Jul*** | 20-Jun |
| Median Annual Peak Discharge | 104 | **107*** |
| 1.05-yr Return Interval (cms)<br>2-yr Return Interval (cms)<br>25-yr Return Interval (cms) | 250.2<br>724.6<br>2144 | 179.9<br>440.6<br>1030 |

This is consistent with the prior work conducted by Graf (2006), such as Table 2, where Graf saw reductions in instantaneous and mean flows. Rise and fall rates were also consistent, showing a decrease in both rise and fall rates in regulated rivers. The high pulse count and duration were also consistent with Graf's results, where high pulse count did not change by much, yet the duration was greatly extended. There was a ~28% decrease in discharge for the 1.05-year return interval, a ~39% decrease for the 2-yr return interval, and a ~52% decrease for the 25-year return interval. A flow duration curve was produced to examine pre- and post-dam flow exceedance probabilities (Figure 7). Examination of the flow frequency curves in Figure 7 also indicates a large decrease in the extremes experienced on the river, with the flashiest flooding events decreased and the low flow events.

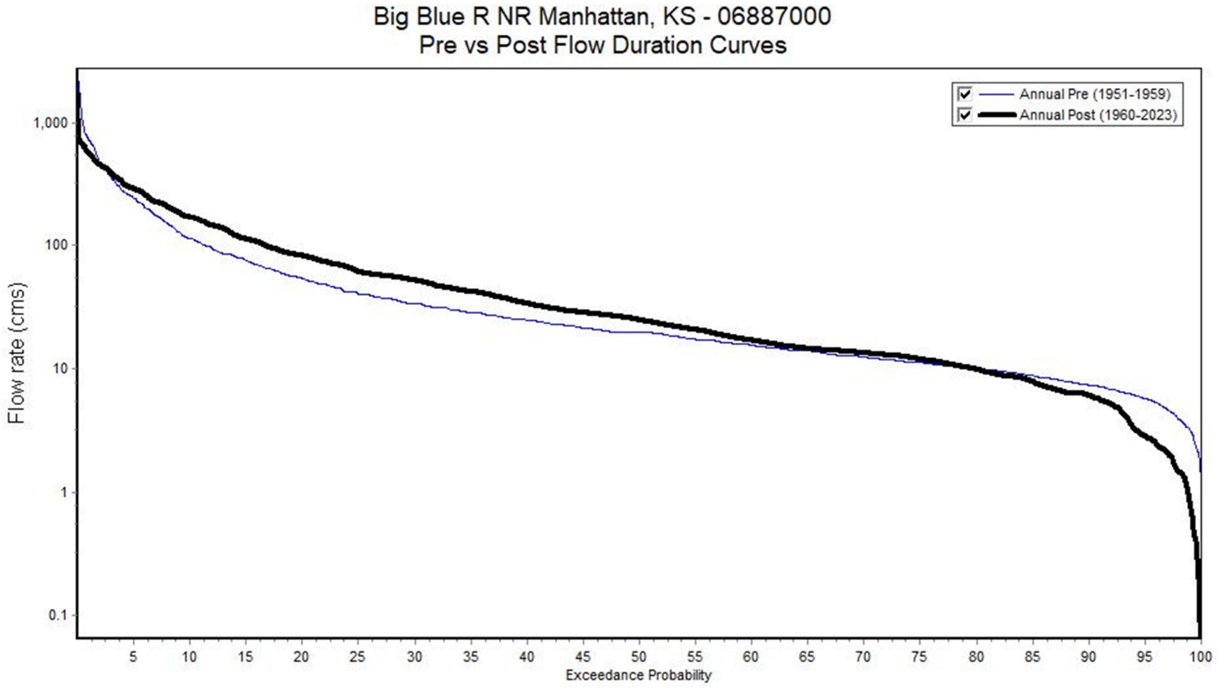

**Figure 6**. Comparison of pre-and post-flow duration curves on the Big Blue River downstream from the Tuttle Creek Dam.

## 4.2 Objective 2: Change in Downstream Bed Stability

Figure 7 shows the change in bed elevation from 1953 to 2022 at the Manhattan Big Blue River USGS gage (06887000). Juracek's (2011) data is represented in blue, while added data from this analysis is shown in red. It is important to note that Juracek's (2011) stream gage height data points at 70.79 cms did not match up with this analysis in 2008 and 2009, as shown in Figure 7. Further investigation is needed to determine why this is.

Figure 8 shows the results from the segmented linear regression analysis. The estimated breakpoints shown in Figure 8 are May 29, 1967, and May 17, 1994, respectively. The estimated linear regression slopes between the breakpoints in Figure 8 are as follows: slope 1 is -0.0070729 m/yr, slope 2 is -0.0407980 m/yr, and slope 3 is -0.0008373 m/yr.

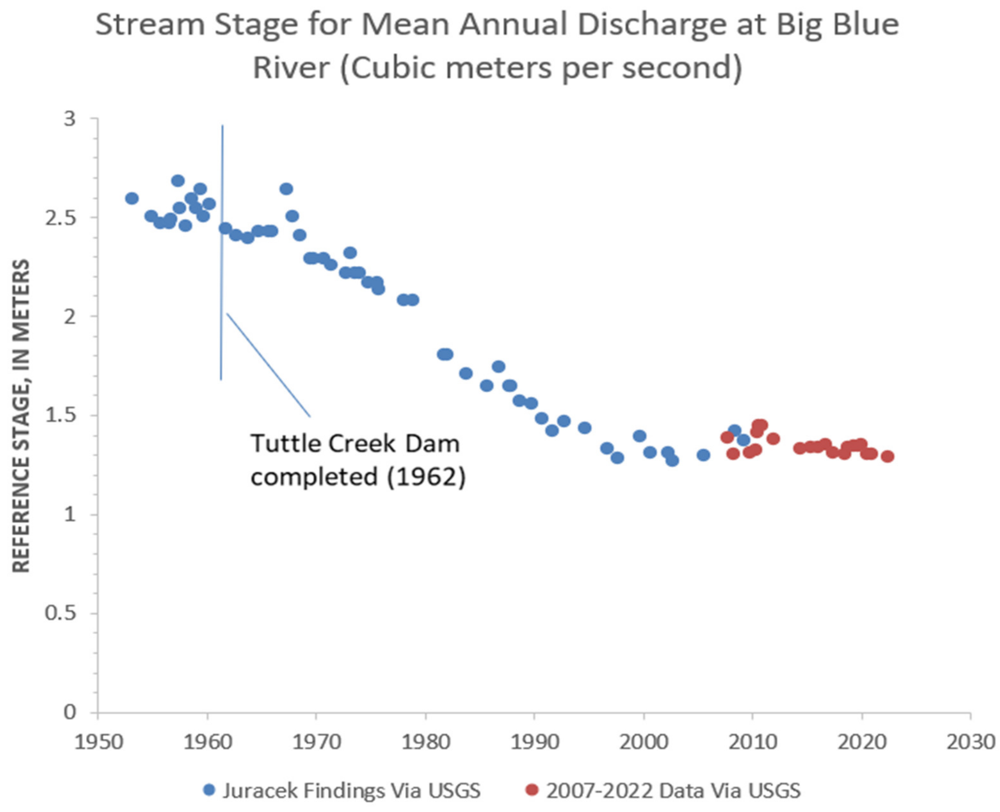

**Figure 7**. Stream stage for mean annual discharge (70.79 cubic meters per second) at Big Blue River near Manhattan stream gage, Juracek graph expanded using USGS gage data from 2007 –2022 (Juracek, 2011). The blue dots represent Juracek's findings from 1953-2010, and the red dots represent data points created using gage height and discharge information obtained from the USGS (U.S. Department of Interior, n.d.).

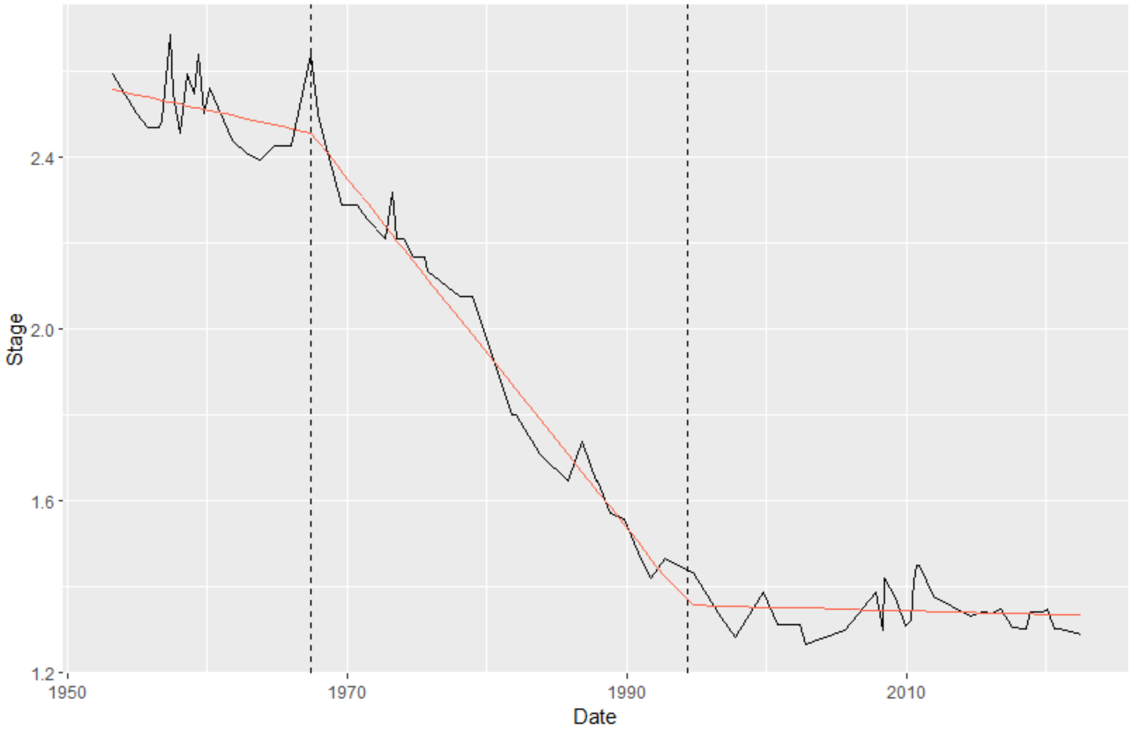

**Figure 8**. Results from the segmented linear regression analysis (red lines) showing breakpoints (dashed lines). The black line represents the reference stage data points found in Figure 7.

The results described here indicate the downstream bed stability of the Big Blue River declined slowly a few years after the implementation of Tuttle Creek Dam in 1962 with a slope of -0.0070729 m/yr till May 29, 1967. The bed elevation declined quickly after this at a rate of -0.0407980 m/yr until May 17, 1994. Since then, the bed has appeared to stabilize (slope = -0.0008373 m/yr). The bed dropped 1.6 meters during the 27-year span (1967-1994), as shown in Figure 8. This finding is comparable with the 35 streams studied in Friedman et al.'s paper, as mentioned in section 1.3, where 11 rivers saw channel narrowing, and 13 saw a reduced channel migration rate. One case with both channel narrowing and reduced channel migration rate. There were nine cases where channel narrowing did not occur; however, there was not enough information to determine the channel migration rate. One final case was where both channel narrowing and migration did not occur (Friedman et al., 1998). The Big Blue bed appears to have stabilized after the highest-ever recorded pool levels at Tuttle Creek Lake in 1993. The Flood of 1993 resulted in the only spillway release in the history of the lake (Tuttle Creek Lake History, n.d.). All eighteen tainter gates were raised 1.2192 meters during the flood's peak, releasing 18,288 cms, a record-high discharge since dam installation in 1962 (Tuttle Creek Lake History, n.d.). However, this is not the record high discharge since gage installation in 1951; this record is 27,432 cms that happened in 1951 (USGS, n.d.). The gates were closed following three weeks of releases, transforming the spillway channel into a canyonland due to the incredible eroding power of fast-flowing water (Tuttle Creek Lake History, n.d.).

### 4.3 Objective 3: Assessment of Downstream, Long-Term Degradation Lines

Channel degradation and widening can be visibly seen in Figures 11 through 13. The newer the measurements, the more degraded, wider, and steeper the banks were found to be. In addition, the fewer measurements, the more unpredictable the results were. Although the initial flow rate and discharge after dam removal were significantly higher than normal, the magnitude of these discharges decreased with later flooding events. This was likely due to the impact of degradation on channel characteristics, as channel degradation results in more unstable channels prone to filling up with sediment. Range E (Figure 9) was likely the least trustworthy of the ranges, as the data had to be manipulated to ensure conformity with the other graphs. Most of the recorded distances for three of the four series were negative. A numerical amount equal to the smallest negative value was added to each distance in the affected series to fix this. As a result, Range E should be considered unreliable.

**Table 4**. A summary of the earliest cross-sectional area and the latest cross-sectional area calculated for each range. Range A was eliminated due to inconsistent results.

| | Earliest Recorded Year | Earliest Cross-Sectional Area (m^2) | Latest Recorded Year | Latest Cross- | Difference in Area (m^2) |
|---|---|---|---|---|---|

|  |  |  |  | Sectional Area (m^2) |  |
|---|---|---|---|---|---|
| Range B | 1961 | 610.88 | 2021 | 980.45 | 369.57 |
| Range C | 1961 | 575.65 | 2021 | 845.32 | 269.67 |
| Range D | 1961 | 653.08 | 2015 | 789.26 | 136.18 |
| Range E | 1961 | 1079.14 | 2021 | 1784.15 | 705.01 |
| Range F | 1961 | 650.45 | 2021 | 867.055 | 216.605 |
| Range G | 1961 | 707.486 | 2021 | 722.99 | 15.504 |
| Range H | 1961 | 817.45 | 1995 | 891.04 | 73.59 |
| Range I | 1961 | 1202.95 | 1995 | 1248.02 | 45.07 |

Two cross-sectional areas were taken of each range. Interestingly, Range E (Figure 9) had the greatest difference in area of all ranges; however, this was likely due to data manipulation limiting the trustworthiness of the data.

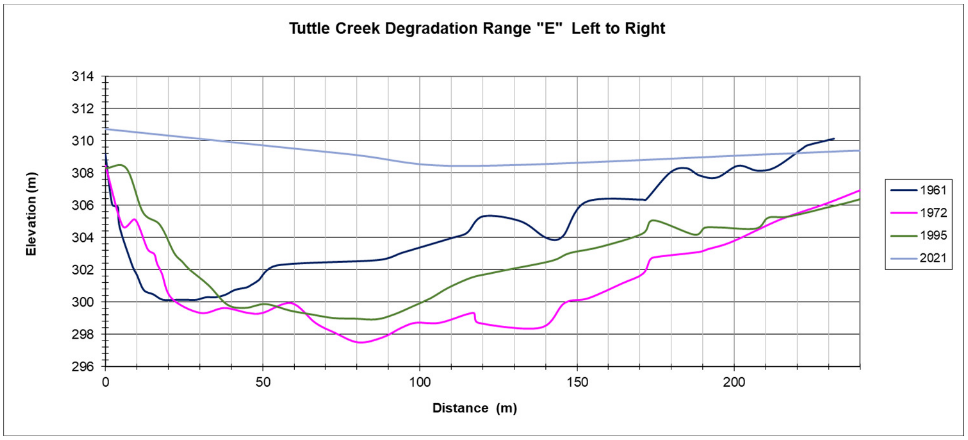

**Figure 9.** River distance and elevation measurements at the banks from 1961 to 2021 of Range E. 494.51 were added to each distance measurement.

Range A (Figure 10) was the only range to have a cross-sectional area from a newer series to be smaller than a cross-sectional area from 1961. This was due to having limited measurements between 22 to 109 meters of distance on the y-axis. Missing data points and uneven sample sizes resulted in inconsistent and strange lines.

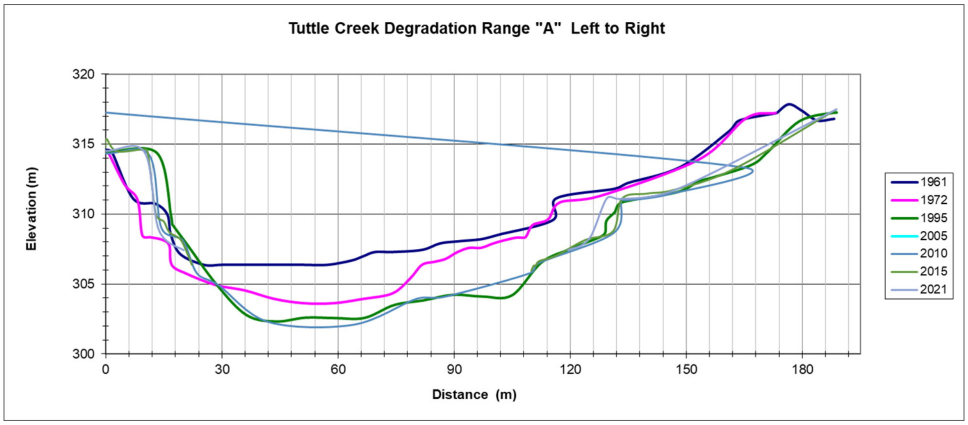

**Figure 10.** River distance and elevation measurements at the banks from 1961 to 2015 of Range A.

Three of the degradation ranges considered were found to best show the presence of stream evolution. These ranges are Range D, F, and I (Figures 11-13). Range D (Figure 11) had the most concise and clear example of channel evolution. As can be seen in Figure 11, both channel banks and the channel widened concurrently throughout the past 60 years. The cross-sectional area difference between 1961 and 2015 was 136.18 m^2. Excluding Range A, this was the th smallest difference in cross-sectional area.

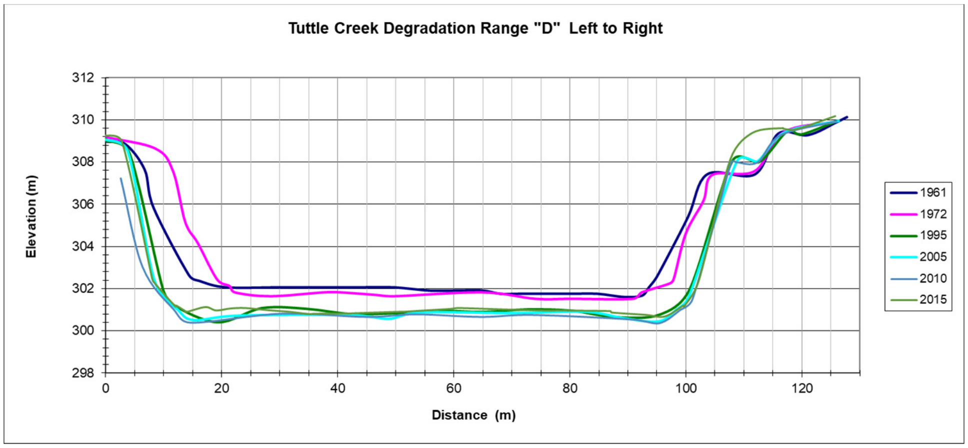

**Figure 11.** River distance and elevation measurements at the banks from 1961 to 2015 of Range D.

Range F (Figure 12) also visibly experienced channel degradation, although this degradation was the most visible on the bed. Both bank and bed degradation occurred concurrently throughout the past 60 years. The cross-sectional area difference between 1961 and

2021 was 216.605 m^2. Excluding Range A, this was the 5th smallest difference in cross-sectional area.

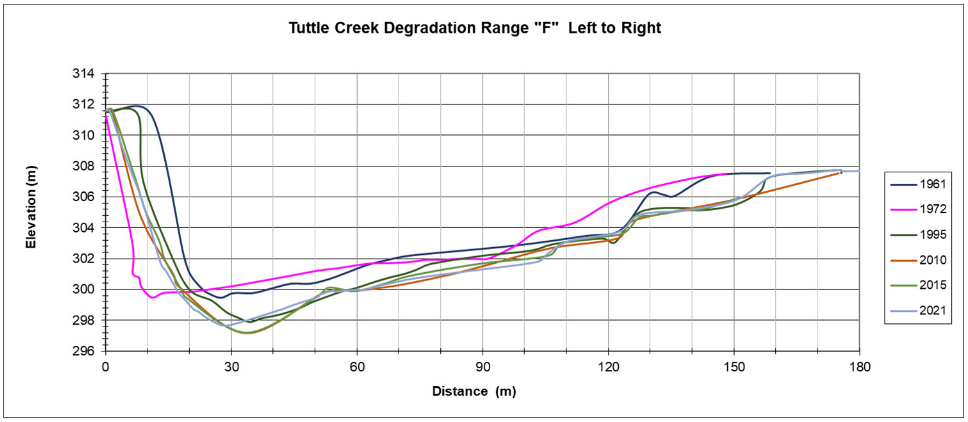

**Figure 12**. River distance and elevation measurements at the banks from 1961 to 2021 of Range F.

Range I (Figure 13) also visibly experienced channel degradation, although this degradation was the most visible on the bed. Both bank and bed degradation occurred concurrently throughout the past 60 years. The cross-sectional area difference between 1961 and 1995 was 45.07 m^2. Excluding Range A, this was the second smallest difference in cross-sectional area.

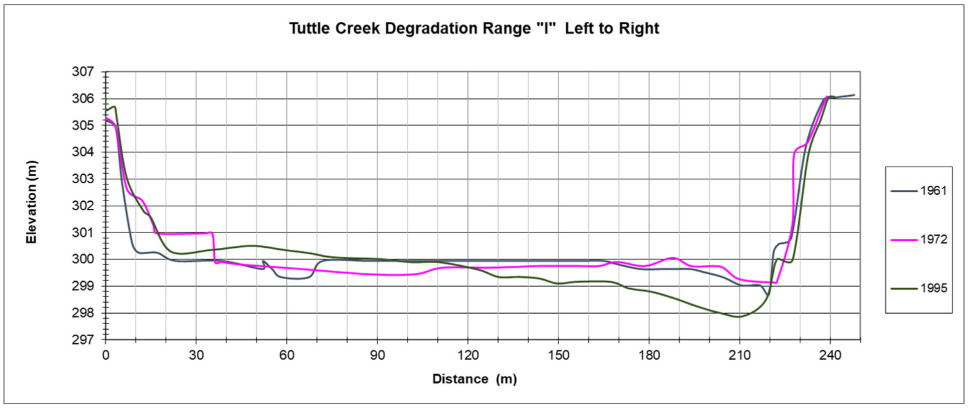

**Figure 13.** River distance and elevation measurements at the banks from 1961 to 2021 of Range I.

## 6. Channel Evolution

As shown in the results presented in the previous section, the river reach downstream of Tuttle Creek Dam has suffered degradation and channel widening over the last 50 years since dam closure. Although channel degradation and evolution are complex, multi-faceted processes, there exist models that can be used to estimate these processes. These are channel evolution models (CEMs), which are intended to predict the effects that disturbances would have on channel morphology (Cannatelli & Curran, 2012). Once developed, CEMs can help river managers prevent further environmental damage and assist in expediting the evolution process (Cluer & Thorne, 2014).

Hydrologists have developed many CEMs, but there are four enduring ones that most relate to the current situation on the Big Blue River: (1) the Schumm model, (2) the Simon and Hupp model, (3) the Stream Evolution model, and (4) the Pearson and Collins model. The Schumm, the Simon and Hupp, and the Stream Evolution CEMs are derivatives of each other, while the Pearson and Collins CEM is simpler than the prior three.

The first CEM is the Schumm et al. (1984), consisting of 5 stages. In Stage I, the channel has yet to be affected by degradation and exists in its pre-disturbance form. In Stage II, bed degradation begins to occur vertically, resulting in a deepening channel. This continues until Stage III where degradation also results in lateral widening of the channel. This process continues throughout Stage IV, with bed aggradation beginning in Stage IV and reaches equilibrium by Stage V, where channel degradation begins to cease, and conditions stabilize.

The Schumm et al. (1984) model has limitations, necessitating numerous additions and the development of updated models. The Simon and Hupp (1987) CEM was the first major modification of the Schumm et al. (1984) model that ultimately became the most popular (Van Dyke, 2013). The Simon and Hupp (1987) CEM is six stages and was created using data collected from West Tennessee streams. This model's stages are called premodified, constructed, degradation, degradation and widening, aggradation and widening, and quasi-equilibrium.

Stages I and II are identical to the corresponding stages in the Schumm model; however, the Simon and Hupp model diverges from the Schumm model at Stage III. In this stage, channel bed degradation continues to occur and results in a deepened bed. In Stage IV, bed degradation continues as lateral degradation results in channel widening. This results in steep riverbanks that are at higher risk of erosion. Channel widening continues in Stage V, but aggradation begins resulting in a higher channel bed. The channel reaches equilibrium in Stage VI, and further degradation does not occur until there is a new disturbance.

The Simon and Hupp model (1987) differs from the previous Schumm et al. (1984) model in three major ways. The first difference is that the extra stage in the Simon and Hupp (1987) model corresponds to common channelization. The second difference is that bed degradation still occurs during bank degradation in the Simon and Hupp (1987) model. The last major difference is that the Simon and Hupp (1987) model places greater emphasis on vegetation than the Schumm et al. (1984) model (Cluer & Thorne, 2014).

Another model was proposed that is called the Stream Evolution Model, and it built on these prior models by including the presence of three additional stages (Cluer & Thorne, 2014). One stage was placed before every other stage and was meant to represent pre-disturbance conditions. The other two stages occurred after the pre-established stages and were meant to represent late-stage evolutionary changes. Unlike the prior models, this model is cyclical and non-linear, which gives it more flexibility, and the extra stages allow the development of a more nuanced understanding of channel evolution (Cluer & Thorne, 2014).

A two-phase channel evolution model exists that was created by Pearson et al. (2011) and Collins (2017). This model focuses on sediment introduction to a disturbed channel (Fields et al., 2021). In this model, dam removal first results in large quantities of reservoir sediment being introduced to the downstream portion of the river. This occurs without the need for a high-intensity flood event, and the channel reaches a point where more sediment can only be introduced through high-intensity flood events (Fields et al., 2021). The first phase is transport-limited, where there is high sediment availability, but the lack of high-intensity hydrologic events limits the movement of this. The second phase is considered to be sediment supply limited, where sediment movement can only occur during high-intensity hydrologic events (East et al., 2018), The effect that this model has on a channel is heavily dependent on dam and soil characteristics (East et al., 2018).

Based on the collected data, the Simon and Hupp model best corresponds to the channel degradation in Tuttle Creek. As both bank and channel bed degradation consistently occurred in tandem throughout the recorded series. Generally, ranges were found to be in Stage IV of the Simon and Hupp model, which is called degradation and widening.

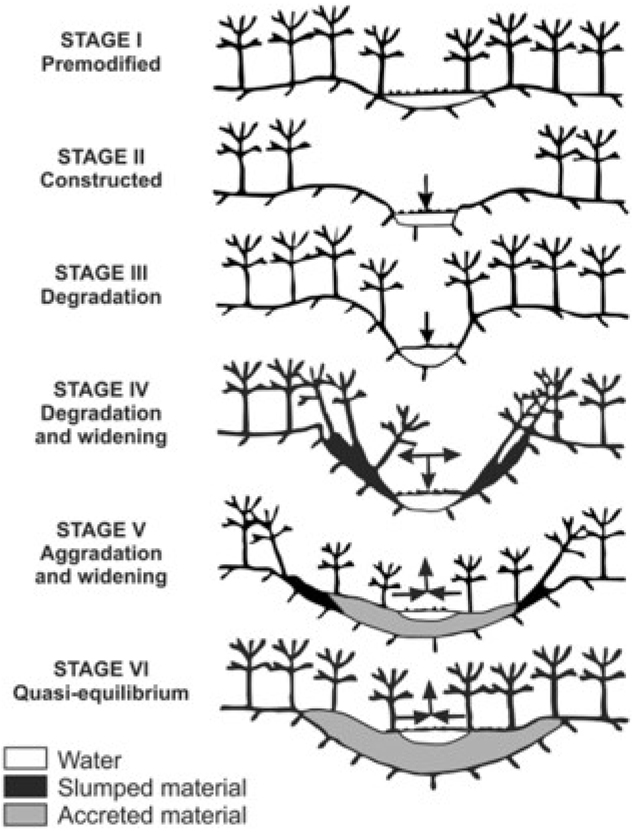

**Figure 14.** A pictural depiction of the Simon and Hupp channel evolution model. Figure retrieved from Cluer & Thorne (2014)

## 7. Conclusion

Stream management relies on successful prediction and understanding of channel degradation, which makes having a cohesive understanding of channel evolution models and other predictive tools important (Booth & Fischenich, 2015). Although we were able to determine how this stream evolved and develop a complex understanding of the Big Blue River, further work must be done on CEMs. Further elucidating channel evolution and the disturbances that create it will be vital in improving stream management and restoration, especially in areas with novel stream evolution or urban areas where most stream degradation occurs.

Dams and their produced reservoirs are essential to local communities, often providing flood control, water supply, hydroelectricity, and/or recreational opportunities. However, dams greatly impact the ecosystems and morphology of the rivers they are constructed on. Dams play a major part in altering the natural erosion of a stream by entrapping sediment that would naturally travel downstream (Juracek, 2011). Dams also alter the downstream incision rates of a stream, leading to increased erosion on the river beds as entrapped sediment does not recharge the new erosion (Williams and Wolman, 1984). Direct effects to the flow and sediment regimes alter the downstream channel morphology (Petts et al., 2005) and its aquatic ecosystem (McCartney et al., 2001).

Statistical analysis of the Big Blue River before and after the installation of the Tuttle Creek dam has shown statistically significant changes in hydrological characteristics, including: median rise and fall rate; median high pulse count and median duration for the post-time period; the median date of annual peak flow for the pre-time period; and median peak flow for the post time period. Flood frequency has also shown to be diminished in the post-time period showing a 28 – 52% decrease in discharge for flood events.

Based on the graph created in RStudio in Figure 8, channel bed degradation of the Big Blue has occurred but has stabilized. Bed degradation seems to have started with the implementation of Tuttle Creek Dam in 1962. In 1967, decline accelerated until 1994 when the bed appears to have stabilized due to the 1993 Flood. Based on the data, the Simon and Hupp model was the CEM that best fit the Big Blue River. In this model channelization was occurring, and both channel beds and banks faced degradation, and aggradation at different stages of the model. The Big Blue River was generally found to have been in Stage IV of this model, although there may be some exceptions to this. Range D, may be in early stages of Stage V, which is aggradation and widening, as the latest series is not as wide as the earlier series.

By understanding a dam's impact on the downstream river channel, river managers can attempt to mitigate some of the harmful effects, as well as generate new and innovative approaches to create sustainable relationships with the downstream aquatic ecosystem. Furthermore, as populations continue to grow, the current state of dams cannot effectively support the future demands of the environment, people, and GDP (Shi et al., 2019). Therefore, when planning new dams, careful consideration of the effects of dams is critical to minimize their potential impacts.

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