Assessing the Impacts of Dams on Nutrient and Sediment Loading in the Kalamazoo River Using the Soil and Water Assessment Tool (SWAT)

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ASSESSING THE IMPACTS OF DAMS ON NUTRIENT AND SEDIMENT LOADING IN THE KALAMAZOO RIVER USING THE SOIL AND WATER ASSESSMENT TOOL (SWAT)

by

Daniel Henry Serfas

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Advisor: Chansheng He, Ph.D.

Western Michigan University
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ASSESSING THE IMPACTS OF DAMS ON NUTRIENT AND SEDIMENT LOADING IN THE KALAMAZOO RIVER USING THE SOIL AND WATER ASSESSMENT TOOL (SWAT)

Daniel Henry Serfas, M.A.
Western Michigan University, 2012

The Soil and Water Assessment Tool (SWAT) was applied to the Kalamazoo River Watershed in order to evaluate the impacts that several dams within a superfund site "Area of Concern" have on the sediment, nutrients, and streamflow of the system. It was hypothesized that the SWAT model could be used to recreate the watershed in hopes of estimating the amounts of nitrogen, phosphorus, and sediment that would result from the removal of the dams. The model would then be used to evaluate dam removal scenarios to come up with a best management practice (BMP).

The model was calibrated, however, during the validation phase the statistical derived accuracy measurements showed that the model was incapable of accurately recreating the conditions found within the watershed. The parameters that dictated the movement of water through the system had been systematically adjusted to rectify this problem without success. Systematic adjustments of the coefficients revealed that no accurate representation of the watershed could be created using the data described in this study. The manual calibration of the model uncovered that in order to produce model values that are similar to the observed data that values which lie outside the range allowed by the model must be used. The use of such values contradicts the actual traits that would result from the data used for the creation of the model.
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Daniel Henry Serfas
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CHAPTER 1

INTRODUCTION

1.1 Background

Throughout human history, dams have provided many important functions. Dams provide protection from flooding, store water for consumptive purposes, provide recreational opportunities, and supply electrical and mechanical power to residents and industry. The benefits and detriments of dams have been debated and documented throughout their history. Many of the dams that reside on our rivers were built prior to the 1960s and done so before the requirement of in-depth studies of their impacts. It was only after the passage of the Dam Construction Approval Act, Public Act 184 of 1963, that required builders of dams to obtain permits and anticipate the impacts of their proposed impoundments (recent amendment Part 315, Dam Safety, of the Natural Resources and Environmental Protection Act, 1994 PA 451). Since then, there have been hundreds of studies done that describe the impacts that singular dams have on components of the environment. Much of this research aims to gain insight into the impact that dams have on wildlife and on the ecology of riverine systems (Crane 2009, Bednarek 2001, Doeg and Koehn 1994). However, many of these studies focus on the impacts of removing one particular structure simply because dams are not removed more than one at a time. Many environmental pundits have been calling for the removal of these structures in order to restore these systems
to their more natural free flowing state (Graf 2002, Hart, et al. 2002). Additionally, with an increasing number of smaller dams exceeding their useful lifespan and their integrity failing, the removal of multiple dams at a time may be needed to cut costs and possibly save lives. Until recently there has been little effort to quantify the cumulative impacts that multiple dams have on sedimentation and water quality (Graf 2002). This is especially true when talking about the use of simulations to obtain information about water quality in regards to impoundments. With recent advancements made in the computational ability of modeling watershed processes watershed modeling looks to become a more useful tool in the data and information gathering process. Despite the large number of methods and models that could be used for quantifying and identifying the impacts of structures there are very few efforts made to standardize the procedures for doing so (Singh, et al. 2004). This becomes even more apparent when researching the removals of small to mid-sized impoundments. In spite of the removal of hundreds of small dams there are very few data which describe their impacts pre- or post- removal. In addition, there is no streamlined process for uncovering the cumulative impacts of these structures in order to justify their removal. This may be because they are typically dismissed as having minimal impacts to their river system due to their size, short residence times and limited storage capacity (Thomson, et al. 2005 and Hart, et al. 2002). These observations contradict the dam related water quality studies done by biogeochemists. Several studies have described that features that reduce connectivity of a waterway are capable of significantly impacting the transport of sediment, nutrients, and
changing the biogeochemical processes within the system (Rueda, Moreno-Ostos and Armengol 2006 and Tockner, et al. 1999).

The problem with many of these water quality studies is that they have required a substantial amount of time and money to complete. A more readily available and complete understanding of the impacts that dams play could help resource managers and government agencies determine the best course of action regarding the removal of impoundments. The use of computers and modeling in this way could produce information regarding the behavior of nutrient and sediments within the newly unobstructed river system.

More information on this topic is coming to light through the use of computer modeling software. As the increasing age, decline in the usefulness, and increasingly high cost of repairing dams have perpetuated the removal of impoundments, ecologists, biologists, and environmentalists are uncovering the benefits of returning rivers to their natural free-flowing state – some of which are using computer modeling processes to complete the task. Hart, et al. (2002), proposed a framework for predicting these benefits based on a set of stressor-response relationships. These relationships spawned much of the ecological and biological research in terms of the impacts of dams. Bednarek (2001), cited that the restoration of unregulated flow regimes to an aquatic ecosystem has resulted in the increase of biotic diversity through the enhancement of perferred spawning grounds or other habitat. In his historical assessment of the Kennebec River in Maine, Crane (2009) highlighted the environmental benefits of dam removal as an important contributor in the river
restoration process. Likewise, Doyle, et al. (2005) looked at a series of small dam removal studies in order to examine how the changes in the geomorphology of the stream channel affected nutrient dynamics, vegetation, and aquatic life. Impacts to aquatic species (mainly salmonids) due to the release and resuspension of sediments and nutrients by dams and their removal was highlighted by Kondolf (2006). The commonality in the studies described above lies in the difficulty of cost and time effectively estimating and identifying the movement of sediments, nutrients, and changes in flow within the river system. Impacts to water quality and quantity will be increasingly easier to predict and recognize as modeling of dam removal becomes more standardized and described. The scarcity of and degradation to freshwater resources as well as concerns of liability in regards to dam failure have made the removal of dams an attractive resolution and the need for understanding the impacts of these structures in a time sensitive manner will be highly valuable.

One of the most common misconceptions about the removal of dams is that if the impounding structure is removed that the water quality and the ecology/biota will improve. There have been many studies on the impacts that dams have on the biota and ecological composition of a waterbody (Doyle, et al. 2005, Bednarek 2001, Nilsson and Berggren 2000, Doeg and Koehn 1994). However, there have not been many studies done to quantify the cumulative impacts that the removal of multiple structures have on water quality. This may be because in many instances, it is difficult to gather a basis for comparison to prove if or how a waterbody is impacted by a dam because there are no pre-dam data available (Zhang, et al. 2010).
1.2 Research Hypothesis

Understanding the current impacts that dams have on the water in the Kalamazoo River watershed would provide valuable information about the function and processes of the system. The relatively long time required for studying a watershed and the comparatively short time of the decision making process is at an impasse. The all-inclusiveness of the Soil and Water Assessment Tool (SWAT) model allows it to be a useful tool to simulate management practices quickly and obtain valuable data that can be used in the decision making process. It is hypothesized that the removal of dams within the Kalamazoo River watershed will negatively impact water quality both short- and long-term despite their relatively small size.

In addition, my efforts should highlight the usefulness of the SWAT model to accurately reproduce the characteristics of the Kalamazoo River watershed, determine the amounts of nitrogen, phosphorus, and sediment that could be expected as a result of various dam removal scenarios and produce a best management practice (BMP) that would allow for the least amount of nutrients and sediment to enter the system based on the systematic removal of impoundments.

I believe that because of this, the removal of dams as a means to improve water quality will actually have a negative impact on water quality both short- and long-term due to the loss of the ability of the impoundments to promote conditions
that cause sequestration – more closely following the work done by Rueda, Moreno-Ostos and Armengol (2006) and Tockner, et al. (1999).

1.3 Objectives

This study is to verify and compare the results of the modeling efforts done by Wells, Langendoen and Simon (2003) on the channel adjustment and sedimentation processes of the Kalamazoo River following low head dam removal. In their paper they used soil sampling to estimate the amounts of sediment that would be released as a result of dam removal within the Kalamazoo River. Additionally, my efforts made use of the SWAT model to determine the loading of nutrients that would occur naturally within the Kalamazoo River watershed. Complimentary to this, the information and data that was created was used to solidify the definition of what the word “healthy” means for the Kalamazoo River and helped to identify the underlying factors that make up a healthy watershed. This refined definition helped to identify the important baseline information that was needed to understand the processes that most greatly impact water quality within the Kalamazoo River watershed.

Many of the attempts at defining what a healthy watershed is are very vague. For example, Guobin, et al. (2002) (p 151) defined a healthy watershed as being a “…system [that] will have a relatively stable structure in which ecosystems function well and in which sustainable development can occur.” A more complete definition of watershed health and the components that determine health have been refined by the Minnesota Department of Natural Resources Watershed Tool website to include the declaration that watershed health may have no basis for comparison (MNDNR 2012).
My research was geared toward refining of the definition of what “healthy and normal” means in terms of the water quality of the Kalamazoo River watershed. This was done by quantifying the impacts that dams have on water quality within the watershed to form a better understanding of the natural processes within the watershed. Had this process worked, recommendations regarding the best method for potential dam removals could have been made based on changes to water quality.

1.4 Project Scope

This thesis used the Soil and Water Assessment Tool program (SWAT) to approximate the water quality conditions found in the Kalamazoo River prior to and following the removal of dams. The simulations will be used to determine the impact that each dam has within the “Area of Concern” of the Kalamazoo River (Figure 1).

The purpose of this research is threefold: 1) to accurately calibrate and validate the SWAT model for the Kalamazoo River watershed so that it may be used as a practical basis for decision making; 2) to quantify the impacts that dams have on the flow, nutrients, and sediment within the Kalamazoo River (both short- and long-term); and 3) to formulate a best management practice recommendation based on the results of the modeled scenarios.
The model was to be calibrated to known streamflow and water quality data. Water quality standards set forth by the Michigan Department of Natural Resources (DNR), Department of Environmental Quality (DEQ), and the United States Environmental Protection Agency (USEPA) were to be used as the thresholds for determining the practicality of each of the scenarios.

The next section of this paper will review the pertinent literature and address the issues relating to dams. A brief introduction to the history of dams and their impacts will be discussed. Immediately following the introduction will be some background information on the Kalamazoo River watershed and its dams. The next section of literature review highlights the studies and modeling efforts regarding dam removal. A description of the SWAT model and its processes follows. The methodology and changes to the standard SWAT modeling process segues into a
discussion about the results of this study. The final section highlights the significance of the findings of this study, provides a conclusion, and cites limitations which may have impacted the outcome.
CHAPTER 2

LITERATURE REVIEW

2.1 Background

Dams have played an important part in the successful development and colonization of various parts of the world. Through the control of rivers by damming, colonists were able to provide reliable water supplies for irrigation, transportation, drinking, recreation, and power production to support budding communities (FEMA 2010). In their infancy, dams were small, crude, and constructed mainly of soil, wood, or stone. The need for power and larger reliable sources of water required to support the growing numbers of residents in expanding manufacturing regions forced the builders to upscale the size of the structures. The increase in the size of the structures required substantial advancements in dam engineering practices. With the increased size came an increase in the area that could be impacted by the structure. However, concerns over the impacts to the area were downplayed as the usefulness of dams was realized leading to their widespread use along many waterways throughout the world. Over 2.5 million dams are currently distributed within the United States alone (O'Malley-Wade 2002). Eighty percent of these structures are low head dams; meaning that they are shorter than 5 meters (16.40 feet) high (O'Malley-Wade 2002). Of the remaining 20 % of dams, the ones that are higher than 10 meters (32.81 feet) – 350 meters (1148.29 feet) are generally the ones that are of concern. The mid-sized dams – between 5 and 10 meters - represent a small but significant proportion of the
dam population and are generally neglected when it comes to research and notoriety. The larger dams (>10 meters) that are responsible for providing power and recreation to countless numbers of people are typically the only structures that cause heated debates over their removal. According to the United States Army Corp of Engineers National Inventory of Dams data, there are currently 743 dams that are shorter than 7.62 meters (25 feet) high in the state of Michigan (USACE, National Inventory of Dams 2010). Most of the dams along the Kalamazoo River are of this size.

2.2 Impacts of Dams

Dam building in the United States began shortly after the arrival of European settlers and continued until its peak in the 1960s. During the 1960s it is estimated that approximately five dam projects were completed every day (Graf 2002). This substantial withholding of flow within riverine systems has resulted in serious impacts to the biology, ecology, and geomorphology of river systems (Hart, et al. 2002, Bednarek 2001, Nilsson and Berggren 2000). Significant fragmentation of ecosystems has generally led to the overall decrease in biodiversity within impounded waterways (Graf 2002). Changes to the physical structure of the river due to the construction of an impoundment cause changes in the distribution of plants, animals, nutrients, and sediment within the system. In addition, dams are one of the leading causes of anthropogenic water quality degradation (Graf 2002).

Several studies have been done on the impacts of dams on the physical parameters of a river system. Yang, et al. (2005) discussed the storage and overall decreasing trend in sediment due to the dams on the Yangtze River in China. As a
result, the Yangtze River delta and the intertidal wetland areas have drastically reduced in size and number (Yang, et al. 2005). The situation as described by Yang, et al. (2005) showed that while the overall amount of sediment that was being lost has significantly increased the amount that has reached the delta has decreased.

An investigation on the impacts of multiple low-head dams on fish, macroinvertebrates, habitat, and water quality in the Fox River in Illinois by Santucci Jr., Gephard and Pescitelli (2005) showed that impounded areas within the river had a lower biological diversity, more degraded biological habitat, decreased native fish populations, and severely impaired water quality.

The impacts of dams on a river is not all bad though. Prochnow, et al. (2007) highlighted the positive impacts of small upland reservoirs on reducing the amount of phosphorus and nitrogen entering the Upper North Bosque watershed as a result of agricultural runoff. The effluent contaminated runoff was corralled behind the impoundments and became sequestered as a result of the reduced flow within the river. The dams were shown to be a cheap and effective method of nutrient reduction in an agriculturally dominant watershed.

Kim, Lee and Kim (2011) showed that valuable knowledge about the impacts of dams could be gained from simply monitoring and modeling the timing and amount of regulated flow leaving a watershed. The impacts of dams could be seen as ecodeficits or ecosurplus and could be used to identify the degree of alteration to the stream. The ecodeficit condition indicated that there was not enough water to meet
the needs of the ecosystem whereas an ecosurplus condition supplied water in exceedance of what is needed by the ecosystem.

The importance of dams in the regulation of nitrogen and phosphorus was shown in the work of Bosch (2008). Bosch’s work on identifying the fate and transport of nutrients following the removal of dams within the Huron and Raisin Rivers in southeast Michigan provided some insight into the mechanisms that control nutrient transport. The use of SWAT in this vein showed that when the dams were experimentally removed from the rivers the amount of nitrogen and phosphorus doubled (Bosch 2008). The dams on the Huron and Raisin Rivers had the greatest impact when they were placed near the river mouth or in higher nutrient source areas. These dams played a vital role in effectively removing excess nutrients.

A statement made by Bruce Babbitt Secretary of the Department of the Interior in 1999 to the Ecological Society of America stated that three-quarters of all freshwater mussels, one-third of all fish, and two-thirds of all crayfish are threatened with extinction due to the fragmentation and degradation of rivers by dams (Babbitt 1999). This statement was made 27 years after the United States passed the Clean Water Act (CWA). The CWA was put into place in hopes of alleviating some of the rampant pollution issues that were causing such uproar throughout the country. The CWA entrusted governmental agencies with the responsibility to “…restore and maintain the chemical, physical, and biological integrity of the waters of the United States” (Clean Water Act of 1972, U.S.C. § 1344 (1972)). Agencies such as the United States Environmental Protection Agency (USEPA) and local entities like the
Michigan Department of Natural Resources (DNR) and Department of Environmental Quality (DEQ), as part of their responsibility per the Clean Water Act, must take every reasonable precaution to ensure that projects that may impact the water supply or water quality are studied and understood to the fullest reasonable extent. Unfortunately, these policies and practices were not in place prior to the construction of many of the dams within the Kalamazoo River watershed. Once these structures are accepted and built there is not much of an effort to produce a standardized method for evaluating the impacts that these structures have while they are in use (Magilligan and Nislow 2005).

2.3 Study Area

2.3.1 The Kalamazoo River Watershed

The Kalamazoo River is located in the southwest portion of the lower peninsula of Michigan. The river stretches from its easternmost reach in Hillsdale County to the western edge of Allegan County where it drains into Lake Michigan near Saugatuck, Michigan (Figure 2). The two main branches of the Kalamazoo River extend across eight counties in a southeast to northwest direction. The north branch of the Kalamazoo River originates in Jackson County while the south branch originates in Hillsdale County. The two branches converge in Albion to form the main branch. The Kalamazoo River is obviously the largest constituent of the Kalamazoo River watershed but there are some other sizable rivers found within its drainage boundary.
The Rabbit River, the Gun River, Battle Creek, Wabascon Creek, and Rice Creek all reside within the Kalamazoo River Watershed. The watershed covers an area over 2,000 square miles and has a discharge rate of roughly 2,200 cubic feet per second (Rheaume, et al. 2003). The Kalamazoo River watershed is approximately 162 miles long, averages around 11 miles wide, and is 29 miles wide at its widest point (Spoelstra 2007). The Kalamazoo River watershed is home to around 400,000 residents and encompasses 19 cities, 11 villages, and 107 townships (Spoelstra 2007).
The glacial history of the region gives rise to the shape of the landscape and the types of soils found within the watershed. The low-rolling moraine topography was carved by several glacial advances and retreats. The average drainage basin relief is approximately 5.58 feet (1.70 meters) per mile with an overall relief of 686 feet (209.09 meters) (Rachol, Fitzpartick and Rossi 2005). The Kalamazoo River watershed’s soils are mainly glacial till and range from poorly drained mucks to well drained sandy loams (Rachol, Fitzpartick and Rossi 2005).

The Kalamazoo River Watershed receives approximately 35.7 inches (906.78 mm) of liquid precipitation annually. During the winter the area also receives 79.7 inches (2024.38 mm) of snow (Knapp 1987). The low-rolling topography and the glacial till soil types indicate that the rivers discharge and height is primarily controlled by groundwater sources rather than runoff.

The Kalamazoo River has many roles within the communities in which it serves. Throughout its history the river has provided its residents an opportunity for recreation, supplied water for irrigation demands, and has been used as a reliable source of hydroelectric power.

2.3.2 Roles of the Kalamazoo River

The watershed has had a very diverse history regarding its use by humans. Paleo-Indians congregated in the Kalamazoo River watershed following the glacial retreat during the last ice age (Wesley 2005). The abundant natural resources and animals in the area spawned many Native American hunting and fishing camps. Archaeological evidence shows that European settlers were setting up fur trading
posts and trapping camps throughout the watershed as early as the late 1600s (Wesley 2005). Stable communities of European settlers formed small cities along the Kalamazoo River in the mid 1800s and beyond. The communities of Battle Creek, Plainwell, and Kalamazoo were all established during this time. The river has played an important role in the economic and industrial development of the region by supporting the need for energy and promoting growth of the mills. The Kalamazoo River was first dammed just prior to the early development of these cities to provide reliable sources of water for irrigation and drinking (Wesley 2005).

2.3.3 The History of Dams in the Kalamazoo River Watershed

The first dam located within the watershed was constructed in the year 1830 and was situated on the north branch of the Kalamazoo River in the area of Concord, Michigan (Wesley 2005). Over the course of U.S. history there have been three main periods of dam construction which parallel the history of dams within the Kalamazoo River watershed. Shortly after the first dam was constructed in 1830 until 1890 there were several small dams that were built to provide power to small, localized grain mills (Rachol, Fitzpartick and Rossi 2005).

After 1890 until about 1940, several larger dams were constructed in order to supply electricity to large paper mills (Rachol, Fitzpartick and Rossi 2005). These paper mills helped to grow the economic base of the cities but also led to significant environmental degradation and contamination within the river. After the closure of these mills the electricity produced by the dams was integrated into the residential power grid and the impoundments resulting from damming were then mainly used for
recreational purposes (Wesley 2005). Subsequently because of their age and inefficiency many of the dams from this period have been retired and are no longer used for their intended purpose. The average operational life span of a dam structure is about 50 to 100 years depending on factors such as sediment deposition rates, streamflow and temperature to name a few (Kondolf 2006).

The final phase of dam construction in the region started in 1945 and lasted until about 1980. During this phase many of the dams that were constructed were used primarily for land development purposes and recreation instead of power production. Many of the cities that sprung up along the river became home to large paper producing mills. The paper mills that were once abundant along the Kalamazoo River routinely dumped waste and other harmful compounds into the river. The discharge of paper mill waste, which contained high levels of chlorinated biphenyls (PCBs) from the recycling of carbonless copy paper, impacted the biota and water quality significantly. In 1970, during routine water testing it was discovered that PCBs were being discharged into Lake Michigan and serious impacts to the biota. The DEQ decided to further investigate these impacts in 1971 with the help of a federal Water Pollution Control Act (WPCA) program which was aimed at monitoring the water quality tributaries of Lake Michigan (U. S. USEPA, EPA Superfund Record of Decision: Allied Paper, Inc./Portage Creek/Kalamazoo River 2001). It took twenty years from that point for the United States Environmental Protection Agency (USEPA) to become concerned enough about the state of the river and its negative impacts on humans for it to designate much of the main reach of the
river a Federal Superfund site in August of 1990 (U. S. USEPA, EPA Superfund Record of Decision: Allied Paper, Inc./Portage Creek/Kalamazoo River 2001). The presence of PCBs along with the dams nearing the end of their useful lifespan has led the USEPA and stakeholders to consider removing some of the structures with the hope of restoring water quality, ecological integrity, and biological diversity. This topic has been debated and several methods have been proposed to assess the impacts that removing these structures would have on the water quality of the watershed.

2.3.4 Major Dams within the AOC – Study Area

There are seven major dams within the Area of Concern (AOC) on the Kalamazoo River. These AOCs were created by the USGS in conjunction with the Michigan Department of Environmental Quality (DEQ) and private entities responsible for the cost of the cleanup. The seven major dams within the AOC are: The Plainwell No. 2 Dam, the Plainwell Dam, the Otsego City Dam, the Otsego Dam, the Allegan City Dam, the Morrow Dam, and the Trowbridge Dam. Three of these structures are scheduled to be removed as a part of the USEPA’s superfund cleanup efforts – the Plainwell, Otsego, and Trowbridge Dams. A fourth structure – the Allegan City Dam has also been mentioned for removal. The Plainwell, Trowbridge, and Otsego Dams were all built in the mid/late 1800s to early 1900s to supply hydroelectric power for Consumers Power Company. These dams remained under the control of Consumer Power until the mid 1960s after which ownership was transferred to the Michigan Department of Natural Resources (Rheaume, Hubbell, et al. 2003). The Plainwell dam consisted of a series of four structures that were built in
1856 to divert water from the main channel of the Kalamazoo River through the mill race of the Plainwell Mill where it was used for the creation of hydroelectric power (Rheaume, Rachol, et al. 2002). The Allegan City Dam was primarily used to supply hydroelectric power until 1997 after which the city of Allegan purchased the structure and upgraded and repaired the dam in 2002 as part of a beautification project for the waterfront (Rheaume, Rachol, et al. 2002).

Table 1 is a compilation of the U.S. Army Corps of Engineers (USACE) National Dam Inventory website which provides a more in depth look at the relative sizes of the dams and their impoundments (see Table 1). These figures were used as data inputs into the SWAT program following the placement of the impoundments.

Table 1: Data from the USACE National Inventory of Dams Website, Source: http://geo.usace.army.mil/pgis/f?p=397:4:595293389135401::NO

<table>
<thead>
<tr>
<th></th>
<th>Allegan Dam</th>
<th>Plainwell Dam(s)</th>
<th>Trowbridge Dam</th>
<th>Otsego Dam</th>
</tr>
</thead>
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<td>1856-1902</td>
<td>1899</td>
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<td>-85.7496</td>
</tr>
<tr>
<td>Max Stor.</td>
<td>20640</td>
<td>1460</td>
<td>660</td>
<td>1530</td>
</tr>
<tr>
<td>Norm. Stor.</td>
<td>17200</td>
<td>490</td>
<td>590</td>
<td>0*</td>
</tr>
<tr>
<td>Max Disch.</td>
<td>26703</td>
<td>5800</td>
<td>14300</td>
<td>3800</td>
</tr>
<tr>
<td>Dam Ht.</td>
<td>30 ft**</td>
<td>21 ft</td>
<td>25 ft</td>
<td>21 ft</td>
</tr>
<tr>
<td>Hyd. Ht.</td>
<td>19.5 ft</td>
<td>14.6 ft</td>
<td>25 ft</td>
<td>18 ft</td>
</tr>
<tr>
<td>Length</td>
<td>1335 ft</td>
<td>1185 ft</td>
<td>440 ft</td>
<td>570 ft</td>
</tr>
<tr>
<td>Drain Area</td>
<td>1550</td>
<td>1299</td>
<td>1522</td>
<td>1474</td>
</tr>
<tr>
<td>Surf. Area</td>
<td>*</td>
<td>56</td>
<td>59</td>
<td>67</td>
</tr>
</tbody>
</table>

* indicates missing data; ** indicates measurement before head removal
The location of the dams within the Kalamazoo Rivers Area of Concern can be seen in Figure 3. The Allegan Dam was excluded from the image because its removal is not currently part of the USEPA's remedial actions.

Figure 3: Locations of the Dams within the AOC on the Kalamazoo River

2.4 Specific Concerns of Pollutants within the Kalamazoo River Watershed

The Kalamazoo River is a major tributary to the greater Lake Michigan basin and as such it plays an important role in the overall water quality of the lake. Pollutants, nutrients, and sediment that leave the Kalamazoo River are of great concern to the overall health of Lake Michigan. Deterioration of the quality of water entering Lake Michigan due to PCB contamination from the Kalamazoo River has been shown to be responsible for the loss of fishing quality and have already cost between $9.4 and $19.8 million dollars in damages (Great Lakes Environmental Research laboratory - GLERL 2011). Additional inputs or releases of pollutants could
have much greater consequences. The estimated total of future recreational fishing
damages are estimated at a range between $3.6 to $10.9 million dollars (GLERL
2011). The Great Lakes region is home to a one billion dollar commercial fishing and
four billion dollar sport fishing industry which helps to support many states and
municipalities tax bases (GLERL 2011).

In addition, recreation and tourism also support a large portion of the
economy of the Great Lakes states. Degradation of water quality would have a
negative impact on these very important industries as well as the 40 million people
that rely upon the lakes as their source of drinking water (GLERL 2011). In addition
to the loss or reduction in the use of these resources due to contamination the major
concern would be the cost needed to remediate such a situation. A pertinent example
of this can be seen in any documentation regarding the Fox River PCB saga and its
excessively gross cost of cleanup (Katers 2004).

Recent reports from the Fox River cleanup saga have highlighted how quickly
the costs of cleanup compound. An article written by Srubas (2011) describes how
two of the companies that were held responsible for the damages spent $300 million
remediating the PCB contamination. These costs accrued from the beginning of 2009
to the end of 2011. Srubas (2011) goes on to state that the estimated cost of cleanup is
around $750 million; which does not include the cost of the damages sought by the
government which could push the figure in excess of $1 billion.
2.5 PCBs, History of Contamination, and the AOC

2.5.1 PCBs

The acronym PCB stands for the term polychlorinated biphenyls. PCBs are oily liquids or solids that are generally colorless, odorless, congeners of 209 similarly similar compounds (Agency for Toxic Substances and Disease Registry - ATSDR 2000). Mixing different combinations of these chlorinated compounds together creates new compound congeners which all have slightly different physical characteristics from one mixture to the next. Although they are slightly different they all have share some fundamental physical properties. PCBs are generally very stable compounds that do not easily degrade, are non-flammable, have high boiling points, and exhibit excellent electrical insulating capabilities (ATSDR 2000). PCBs have been used in many types of electrical devices and equipment due to their physical characteristics. PCBs have been found in electrical transformers, capacitors, voltage regulators, fluorescent light ballasts, and electrical insulation. PCBs have also been used as an additive to adhesives and tapes, oil-based paints, caulks, plastics, and flooring finishes (ATSDR 2000).

The different mixtures of PCBs are described using a numbering system which indicates the specific PCBs that are in the mixture. The trade name Aroclor™ (Monsanto 1935) followed by a four digit number is generally used to specify the locations and amounts of chlorination within the individual PCBs in the mix. This trade name information is particularly important when doing a clean-up of PCBs to ensure that the correct pollutant is treated for.
2.5.2 PCBs, Nutrients, and Sediment Interactions

Increased oxygenation - like what could be seen following the restoration of a river to a free-flowing state - has been predicted to cause the release of phosphorus from sediment into the water column (Nürnberg 1988). Stagnant and slow moving water allows for the sequestration of nutrients like phosphorus by reducing the amount of oxygen that is dissolved within the water column. These oxygen reduced (anoxic) conditions are favorable for the formation of organic based components and metallic colloids which tie up limiting nutrients such as nitrogen and phosphorus before they are capable of being used. In addition to facilitating the tying up of nitrogen and phosphorus, these anoxic conditions are also favorable for retaining PCBs. PCBs and nutrients adhere to sediment under anoxic conditions where they may then become reduced by microorganisms; this process lessens the amount of PCBs that make their way into the water column (Manahan 2005). Lake sediments have been shown to act as a time released source of PCBs to the water column and the atmosphere (Larsson, et al. 1990). Within the Great Lakes system, many toxic substances are capable of reaching critical concentrations due to the small percentage of lake waters that are flushed from the system annually (Adriaens, et al. 2002). Desorption of PCBs from sediment is caused and increased by the transport of surface sediment by water (Larsson, et al. 1990).

PCBs are detrimental to many forms of life and have been shown to cause serious environmental and biological problems. These problems will increase in frequency as sediments bound with PCBs are released following the removal of
impoundments. Exposure to PCBs has been shown to spawn numerous undesirable health effects (ATSDR 2000). PCBs have been shown to cause cancer in animals and are considered potentially carcinogenic to humans. Research has determined that humans and animals exposed to PCBs has increased the risk factor for non-Hodgkin’s lymphoma, caused immune system suppression, and induced a number of reproductive, neurological, and endocrine disrupting effects (United States Environmental Protection Agency 2008).

PCBs have demonstrated undesirable impacts to plant life as well. Plants are also susceptible to accumulating PCBs from sediments and the water column. PCBs have been shown to disrupt the plants growth rate by inhibiting cell division and photosynthesis (Zaranko, Griffiths and Kaushik 1997). Bioaccumulation can occur within the food web when plant eating animals consume the contaminated plants and then these primary consumers are then eaten by larger consumers. This process allows the contaminants accumulated by the plant life and the smaller consumers to be concentrated within the larger consumers in the food web. Zaranko, Griffiths and Kaushik (1997) determined that the bioaccumulation of PCBs occurs mainly through the ingestion of the organisms that make up the lower levels of the food web.

Nutrients such as nitrogen and phosphorus are also capable of inducing unwanted health effects within humans and the environment. High amounts of nitrogen within drinking water have been associated with adverse pregnancy outcomes and the production of compounds that cause or aggravate cancer (USEPA: Surface Water Standards and Guidance 2012). In addition, increased growth of
cyanobacteria can produce algal toxins in the presence of excess nitrogen and phosphorus. The substantial blooms of cyanobacteria are capable of producing compounds that are toxic to humans, pets, and livestock (Codd, Morrison and Metcalf 2005). Some of these toxic compounds accumulate in filter feeders like clams and mussels and once they are eaten by other animals they can cause illness or death (Bushaw-Newton and Sellner 1999).

The removal of dams can reduce the number of cyanobacteria through dispersion which may be detrimental because the cyanobacteria process nitrogen and phosphorus which may significantly reduce the load found within the river system. These cyanobacteria may be detrimental to other water quality parameters but they are generally beneficial in controlling nitrogen and phosphorus.

2.5.3 History of Contamination

The bulk of the contamination within the Kalamazoo River watershed occurred approximately a half century after the construction of the dams. These structures that were used to provide electricity and mechanical power to the growing economic base unintentionally became a blessing and a curse in the contamination of the watershed. Paper mills which dotted the banks of the river began discharging PCB contaminated paper pulp and effluent into the river starting in the 1950s (Rachol, Fitzpartick and Rossi 2005). Even though there have not been any inputs of PCBs into the system in decades the sediments and residual paper wastes continue to leach PCBs into the water column. The PCBs were used in the recycling of carbonless copy paper at many of the paper mills that were in the area. Many of the methods that were
used to dispose of the byproducts of the recycling process led to the widespread contamination of the sediment near the mills. The contaminated sediment and paper wastes matriculated downstream and collected along the banks and behind the dams. The frequency and location of the dams helped to corral the contaminants and slowed the spread of PCBs into Lake Michigan. In addition, the slowing of water as it entered the reservoirs reduced the carrying capacity of the river and allowed many of the PCBs to settle to the bottom of the impoundments. The features of the river, the banks, floodplains, wetlands, and much of the in-stream sediments became heavily contaminated with PCBs which caused irrevocable harm to aquatic biota and impacted many other animals that rely on the river for food or water (Wesley 2005).

2.5.4 The National Priority List and Designation as a Superfund Site

For many years, the PCB waste that was created as a byproduct was discharged into the wetlands, channels, and tributaries that feed into the Kalamazoo River. In the 1970s the DEQ conducted routine water sampling near the mouth of the Kalamazoo River and discovered that PCBs were being discharged into Lake Michigan (Wesley 2005). Subsequent biological monitoring was used to determine that the PCBs that were being discharged were significantly detrimental to the biota of the lake and watershed. The severity of the contamination and the lack of an identifiable party to partake in the cleanup led to 80 miles of the river to be placed on the USEPA’s National Priority List.

The DEQ conducted a search to identify potentially responsible parties (PRPs) in 1990 and uncovered three corporations that could be held liable for the PCB
contamination. Plainwell Paper, Inc., Georgia-Pacific Corporation, and Millennium
Holdings/Allied Paper, Inc. were identified as the parties that were responsible for the
vast PCB contamination in the watershed (Wesley 2005). The DEQ and EPA notified
the PRPs of their responsibility in rectifying the contamination and an agreement had
been reached which aimed to control the sources of PCBs. The remedy proposed by
the DEQ and EPA did not include a treatment to reduce the toxicity or directly
diminish the mobility of the PCBs and sediment to which it was attached. The ability
to understand the dynamics of sediment after the removal of the dams through
modeling may provide another way to produce viable remediation solutions.

2.5.5 The Area of Concern (AOC)

As part of the investigation, the EPA and state agencies (DEQ and DNR)
discovered that the PCBs were found downstream of Morrow Dam all the way to the
mouth near Saugatuck, Michigan. This 80 mile stretch of the main branch of the river
became the focus of the restoration and cleanup efforts. In order to expedite the
cleanup and highlight the restoration progress the AOC was divided into smaller
operational units. Each of these operational units has its own management plan to
facilitate the remediation of specific concerns within it. The majority of the sizable
impoundments remaining in the Kalamazoo River watershed reside within the AOC.

2.6 The Cleanup and Restoration Process

The EPA and DEQ in conjunction with local groups have coordinated efforts
to restore the Kalamazoo River. As a part of the restoration and remediation program
the agencies provided a list of eight beneficial uses that are being impaired by the
contamination. The impairments to the beneficial uses form the foundation of the remedial program of the state agencies and EPA. These impairments include restrictions on fish and wildlife consumption, degradation of fish and wildlife populations, animal deformities or reproductive problems, degradation of benthos, - the collection of organisms living on or in sea or lake bottoms (Merriam-Webster, Benthos 2012) - restrictions on dredging activities, beach closings, degradation of aesthetics, and loss of fish and wildlife habitat (U. S. USEPA, Great Lakes Areas of Concern 2011). The goals of the remedial activities are to restore and improve the watershed to a state which these impairments are no longer significant. As part of the remedial activities the EPA, DEQ, and DNR decided that the due to the age of the structures and the excessive cost of restoring the dams that the structures should be removed. The main issue with removal of the dams is the contaminated sediments that lie behind them. Reducing the amount of PCB contaminated sediment through careful planning and mitigation activities are paramount for attempting to restore the impaired beneficial uses.

A hydrologic modeling program called the Soil and Water Assessment Tool (SWAT) was used in conjunction with transect sampling to quantify the amount of sediment that lie behind dams in the AOC. In 2007, the SWAT model was unsuccessfully completed for the downstream half of the Kalamazoo River watershed as an effort to calculate the sediment contribution of sub-watersheds to the main channel (Safferman, et al. 2007). The author mentioned that the difficulty of correlating the SWAT produced values to the USGS data may have been a result of
the number of dams located on the river. One of the goals of my research was to complete the efforts made by Safferman, et al. (2007) and successfully use SWAT for evaluating water quality in the Kalamazoo River watershed. My approach will focus its efforts on completing the evaluation of the downstream section as well as the area upstream of the AOC.

2.7 Dam Removal as a Means for Restoration

The restoration of dammed river systems to a free-flowing state has many potential benefits as well as many drawbacks (Bednarek 2001, Tahmiscioglu 2004, Doyle, et al. 2005). One of the most negative impacts of dams is eutrophication. Eutrophication can occur when excess nutrients are released into a system which causes an extreme period of plant growth which will eventually devoid the system of dissolved oxygen (Bennett, Carpenter and Caraco 2001). In addition, excess nutrients that occur from dam removal may cause a loss of biodiversity and increase the occurrence of nuisance algal blooms which create unpalatable water for people and wildlife (Bennett, Carpenter and Caraco 2001). Thus, dam removal may serve as a mean for restoring health to a water body.

However, dam removal must be carefully planned for, studied, and thoroughly understood in order to elicit the type of responses that are desirable. After all it is generally the ratio of wanted results versus the unwanted that dictate whether the project was successful. It is important to obtain more in-depth information in order to understand the impacts that dams have at a watershed and even sub-watershed scale. Understanding how a dam (or dams) impacts a watershed can help resource managers
and government agencies better understand the dynamics of sediment and nutrients within their watershed. This could also help define the probable response of the watershed to pollution. More comprehensive knowledge of how the physical characteristics elicit responses within a watershed could reduce the time needed to study and clean up an area. Once the underlying factors that drive the system are understood more completely watershed modelers could focus on creating standardized sets of parameter changes for different watershed conditions.

2.8 Evaluation of Watershed Health by Modeling

Recently there have been several tools that have been developed by government agencies to determine if projects are going to impact the quality and safety of a nearby waterbody. One of the most useful tools used for determining changes in water quality is water modeling programs. These modeling programs are able to simulate changes made to the watershed without any actual physical changes taking place. This process is advantageous because it allows the user to “try out” multiple management decisions very quickly and efficiently. Modeling software is capable of making virtual changes because the software uses established physics-based approximations of real world conditions.

Many of the complex physical processes that occur within a watershed can be represented by physics-based mathematical equations (Daniel, et al. 2011). These equations are used to generalize the types of conditions that are found and can be used estimate the response to the changes that occur. These changes can be made to individual sub-watersheds or to the entire watershed as a whole. Through the use of
mathematical equations to approximate real world physical parameters, changes can be made to many of the variables virtually (without any real world physical changes actually taking place) within the watershed.

For instance, the SWAT model has been successfully applied to determining the impacts of various agricultural and land use management practices (Betrie, et al. 2011, Bulut and Aksoy 2008, Migliaccio, Chaubey and Haggard 2007). Adjusting data that are input into the program allows resource managers and decision makers the chance to explore different management scenarios. This process allows experimentation when coming up with an appropriate method or plan to ensure the safety and quality of water resources. Numerous changes can be made to the virtual watershed either incrementally or all at one time. Many of the physically based parameters that are found in watershed models like SWAT, such as land cover type, agricultural practices and precipitation can be changed in order to best represent the area under investigation. These computer programs are often coupled with Geographic Information Systems (GIS) to help decision makers visualize data so that a more complete understanding of the processes that take place within the waterbody can be gained. The use of GIS in this manner provides a convenient platform for incorporating various modeling programs.

2.9 Ecological, Biological, and Water Quality Studies

Ecological studies on the impacts of dams on different populations of aquatic and mammalian species have been generally successful at linking the fragmentation of waterways to reduced populations of many of these species. Studies by Ligon, et
al. (1995) and Nilsson and Berggren (2000) cite that changes to the physical characteristics and sediment/nutrient dynamics of a river ecosystem cause the loss of spawning grounds for fish and other aquatic species. In addition, biological based studies like the one done by Bartholow (2005) show that the decrease of aquatic populations may actually be due to the changes in water quality rather than the result of fragmentation. This dual edge sword of fragmentation and degradation of water resources make estimating any aspect of recovery of an ecosystem very difficult.

The importance of understanding the impacts of these dams is paramount because many of the structures that were built during the 1940s through the mid-1960s - the “Golden Age” of civil service projects - are nearing or are at the end of their useful lifespan. Resource managers, biologists, ecologists, and environmentalists have pushed for the removal of these structures in an effort to return rivers to their natural, free flowing state with the hopes of increasing biodiversity and improving water quality.

Recently, researchers have fashioned studies to bring to light the effects that watercourse altering structures have on subjects within their specialty. In a study about these impacts Tahmiscioglu (2004) generalized that... “dams cause the destruction and loss of archaeological and historical places, destroy the spawning grounds of fish and deter their migration upstream, starve the lower reaches of rivers of nutrients and sediment, and cause the loss of water from evaporation due to the increase in surface area of the reservoir” (pgs. 762-763).
Other ecological and biological studies such as those from García de Jalón and Gortázar 2007 and Doyle (2005) have helped to popularize the idea of dam removal as a means of restoring ecological integrity and biological diversity. These studies have been met with mixed criticism. Proponents of dam removal have generally stated that restoring water quality will lead to an increase in biodiversity. Opponents to this cite that better water quality (in terms of agency imposed standards) does not necessarily correlate to optimal conditions for biota. Therefore, it is important to separate the idealism that directly links water quality to increased biodiversity and thus ecological health. As it relates to this project, water quality is the only factor that can successfully be estimated using a modeling program. My opinion is that the return of biological diversity can only be speculated and is not the focus of this study.

The thinking behind my study follows the trend of the opponents of dam removal. Much of the literature regarding dam removal states that the removal of the structures will positively impact the water quality and thus the biota of an ecosystem (Thomson, et al. 2008). This contradicts the agricultural and water quality studies which have determined that impoundments offer the opportunity for the sequesterization of nutrients and sediments which would improve water quality. This important research done by Prochnow, et al. (2007) described that the removal of dams caused a significant increase in the loading of nitrogen and phosphorus into the Waco Lake catchment in central Texas. This is a significant finding because the dams that were studied were significantly smaller than the ones proposed for removal within the Kalamazoo River watershed and had a very short water retention time.
Increased retention time within waterbodies has been shown to promote sequestration of nutrients through two main processes: 1) The slowing of water allows for nutrients associated with sediment to dissolve due to the reduced carrying capacity of a slower discharge (Rueda, Moreno-Ostos and Armengol 2006); and 2) Reductive geochemical and biogeochemical processes that are capable of helping to sequester nutrients like nitrogen and phosphorus generally take place under anaerobic conditions. Under these conditions microbes convert the nutrients into their elemental form which decreases their bioavailability. The bioavailability of a substance is the degree and rate at which a substance is absorbed into a living system or is made available at the site of physiological activity (Merriam-Webster 2012). Much of the nitrogen that enters the waterways of the world results from the overuse of fertilizers. Nitrogen fertilizers which contain compounds such as ammonium nitrate, sodium nitrate, anhydrous ammonia, and urea are water soluble which makes them available for increased eutrophication.

Nitrogen enters the water cycle through the breakdown of organic materials and through agricultural practices. Generally these conditions are only associated with waterbodies that are thermally stratified throughout the year and do not undergo a complete mixing of their lowest layers (Ottosson and Abrahamsson 1998). The removal of dams reduces the depth of the waterbody and increases the flow of the river. This practice promotes mixing of the water and substrate thereby increasing the oxygen levels in the water and decreasing the amount of sequestering that can take place.
2.10 Watershed Recovery

Impoundments have long been known to alter the physical characteristics of the water bodies in which they reside. The presence of an impoundment causes water to slow down when entering and leaving the artificial environment. This slow down of water can give rise to various biological, chemical, and physical changes. Dams can induce the sequestration of nutrients by increasing the residence time of water and cause the increased rates of sedimentation due to reduced flow rates behind the reservoir. The increased rate of sedimentation occurs as a result of the faster moving water from upstream reaches being slowed by the impoundment. The result of this slowing is the reduced capacity for the transport of suspended solids and bedload from upstream reaches. In addition, the reduced flow rate causes an increase in retention time which allows for these sections of slower moving water to act as nutrient sinks by withholding nutrients and sediments from areas downstream (Craft and Casey 2000, Nürnberg 1988). The reduction in discharge allows for the sedimentation of small particles such as silts and clays which play an important role in sequestering nutrients and improving water quality (Craft and Casey 2000).

The cost of repairing dam structures often exceeds the cost of removing them, which only adds to the lure of their removal (Johnson and Graber 2002). However, some of the information which is used by resource managers to determine how dam removal will impact a river shows conflicting results. Studies done by Doeg and Koehn (1994) as well as Rathburn and Whol (2001) uncovered that fish and macro-invertebrates have the ability to recover to pre-dam conditions but only if efforts are
taken to create similar habitats to those that were present prior to dam construction. Results published by Doyle, et al. (2005; p 240) seem to show the opposite; “…dam removal does not always result in (ecosystem, habitat, and geomorphological) returns to pre-dam conditions.” These differing findings are not necessarily detrimental for dam removal proponents or opponents, what this highlights is the importance of gaining every available source of data (and using the best available technology) to help the decision making process. As Doyle, et al. (2005; p 240) stated “Weighing such costs and benefits of dam removal is important prior to undertaking a project…variable recovery scenarios must be understood and successes and failure should be based on the outcome that is expected.”

Oftentimes the success or failure of a project is based solely on very few parameters. Did the fish return? Did the water quality improve significantly? If the answers to these questions are “No” then the project is often considered a failure. However, if unexpected biodiversity takes place and water quality is not any worse off, should that be considered a failure? Or conversely, if biodiversity decreases but water quality parameters improve should that be considered a success? These milestones and benchmarks that determine whether or not a dam removal project has been successful hinge on this definition of what is considered a success or failure.

While it is important to forecast and plan for the return of species with the hopes of increasing the biodiversity of a riverine system following a dam removal, it is also important to understand that the removal of these structures does not ensure that such changes will take place. It must be understood that water has a function as
both a resource and a habitat and the connectedness of these functions give rise to the
difficulty in improving their health. It is this interconnectedness that makes it nearly
impossible to have enough foresight to predict the impacts and changes that may
occur within a system following an extreme change like a dam removal. The
interconnectedness of the biota and the water quality is not linear and since pre-dam
information does not exist (in many cases) it is important to try to understand as much
about the region undergoing the change as possible in order to minimize the
likelihood of unwanted outcomes. Hydrologic modeling provides an opportunity to
uncover some of the causal relationships of the components within watersheds while
exploring management decisions.

2.11 SWAT and Modeling

The Soil and Water Assessment Tool (SWAT) model (Arnold, et al. 1998) is
the result of multiple modeling efforts made by the United States Department of
Agriculture (USDA). The SWAT model was developed in an effort to predict the
impacts that various land management practices have within watersheds. These
efforts focused on the ability of the model to estimate how changes within the
watershed influence the amounts of sediment, water, and agricultural chemicals vary
with changes to land management practices. The physically based model relies on
various data inputs associated with the movements of sediment, nutrients, and water.
The SWAT model requires readily available information about land use/land cover,
management practices, weather, soil, and topography. The information that is needed
to run the SWAT model is commonly gathered data by government agencies and is
easily accessible. However, some of the required information can be estimated and extracted from data tables that reside within the model.

Many of the hydrologic models that have been created have their foundations in the early works of Darcy (1856), Manning (1891), and Horton (1933). Darcy’s Law generalizes relationship between the volumetric flow rate of a liquid through porous media using the parameters flow area, fluid pressure, and elevation. Robert Manning’s equation is often employed to estimate open channel flow within rivers, regardless of their size. The Manning’s equation uses the velocity, flow area, channel slope, hydraulic radius, and a roughness coefficient of a open channel to estimate the discharge of a waterbody. Horton’s equation is one of the main equations used to measure the rates or volumes of ground infiltration.

There are many different models that use these or similar equations to approximate the ground conditions that are found within a waterbody. The Water Quality Analysis Simulation Program (WASP) (Ambrose, Wool and Martin 1993), Better Assessment Science Integrating Point and Non-Point Sources model (BASINS) (Lahlou, et al. 1998), Agricultural Non-Point Source Pollution model (AGNPS) (Young, et al. 1989) are all examples of models that use the Manning, Horton, and Darcy equations to approximate real world conditions. In addition to being able to recreate the real world conditions of a waterbody, these equations can also function to calculate Total Maximum Daily Loads (TMDLs) and predict non-point and point source pollution transport within a watershed.
TMDL calculations are used by the USEPA and state agencies to estimate the amount of pollution that a watershed can receive and still comply with water quality standards (USEPA 2000). These TMDL calculations are the basis for much of the licensing and water quality guidelines in regards to sediment and nutrient loading. Each of the watershed modeling programs have slightly different sets of data requirements and equations that they use to produce outputs. These differences determine the effectiveness, limitations, and suitability of the models for different applications.

SWAT was originally created as a process-based watershed model developed to quantify the impacts that agricultural land management practices have on water quality within large complex, watersheds. Since its beginning as an agricultural tool, SWAT has branched out and been used for other applications. In the recent past, SWAT has been applied to estimate base flow and groundwater recharge (Arnold, Muttiah, et al. 2000), assess nutrient transport (Geying, Ge and Feng 2006), and understanding the impacts of water projects on river flow regulation and water quality (Zhang, et al. 2010). SWAT has also been used to evaluate best management practice scenarios (Ullrich and Volk 2009; Bracmort, et al. 2006), explore suspended load changes (Kliment, Kadlec and Langhammer 2008), and modeling climate change impacts on hydrology and water quality (Shrestha 2011). These projects highlight the flexibility and usefulness of the SWAT model.

In 2007, an article written by Gassman et al. discussed the applications that SWAT has been used for and gave an extensive overview as to the development of
the program and some of its tools. The SWAT model is highly recognized and used throughout the world. The pervasive use of SWAT is evident when looking at the SWAT users website. A search of the literature database within the website displays 886 articles from various locations which represent physical conditions found all over the world. Because SWAT is so widely used there are a vast number of users groups and help forums worldwide which have helped to debug the program and offer suggestions regarding the use of SWAT under various conditions.

2.12 Structure of SWAT

The Soil and Water Assessment Tool (SWAT) was created to be a watershed scale model that runs on a continuous, daily time step. SWAT’s ability to predict the impacts of management scenarios on agricultural chemical yields, sediment, and water discharge results from the structure of the model and the breakdown of the components within.

There are many components that go into the structure of the SWAT model. These components include hydrologic, plant growth, nutrient and pesticide cycles, as well as land management practices and soil parameters (Gassman, et al. 2007). SWAT uses some of these parameters to separate the watershed into smaller sub-watersheds. These sub-watersheds are further broken down into Hydrologic Response Units (HRUs). These HRUs represent the smallest, most homogeneous combinations of land use, land management, and soil parameters that have the most similar characteristics. The HRUs are based on percentages or predetermined amounts of area of the watershed. HRUs are compiled from the model inputs but are not linked or
related spatially to the ground conditions. The idea of HRUs may seem strange because they lack a geographic component that links data together; however they provide valuable information about the conditions that dictate the movement of water within the system. These HRUs help to identify the parameters impact the movement of water through the system which helps with the calibration of the model.

The model is capable of generating some of its own parameters in order to run a simulation. Climatic inputs are one of those parameters that are commonly generated in areas that do not have (or have incomplete) weather data. Daily climatological data can be simulated by the model based on tables of monthly climate data that are embedded within the program.
CHAPTER 3

METHODOLOGY

3.1 Introduction

The structure and methodology presented in this paper follows the work done by Wells, Langendoen and Simon (2003), Prochnow, et al. (2007), Tullos and Grant (n.d.), and Bosch (2008) during their assessment of the impacts that dams have on watershed components. Bosch’s work with SWAT to estimate the nutrient and sediment loads that would result from the removal of dams within the Raisin and Huron watersheds was used as a guideline for the prioritizing and choosing the order of dam removal (Bosch 2008). The reasons for prioritization was laid out and described in Prochnow, et al. 2007. Wells, Langendoen and Simon (2003) introduced the basic structure and layout of the dam removal scenarios and the workflow that was used in this paper.

The prioritization for dam setup in SWAT by Prochnow, et al. (2007) described the process of modeling the reservoirs as wetlands in SWAT. There are two settings within SWAT to create the reservoirs. These settings either recreate the reservoirs to act as “ponds” or as “wetlands”. Due to the short residence time of the water Prochnow, et al (2007) employed the use of the “wetlands” option because it
has a hard-wired residence time of 10 days which was similar to the amount of time that the dams in his study region had.

Wells, Langendoen, and Simon (2003) introduced the concept of the dam removal scenarios. They used the AOCs created by the USGS and USEPA to estimate the amounts of sediment and nutrient that were likely to be released as a result of dam removals in the Kalamazoo River. During their investigation it was discovered that the dams in simulation resulted in a net transport of 10,500 tons/year whereas the dams out scenario produced 30,100 tons/year.

3.2 Limitations of Data and Data Availability

In order to fully understand and assess the impacts that dams have on the components of an aquatic environment, it is important to understand the conditions that existed prior to dam construction. Obtaining critical information about the status of waterways before an impoundment was created is very difficult to do for three reasons. First, little information was collected on the state of the environment prior to when these dams were constructed because in many cases it was 50 or more years ago. Second, environmental regulations did not exist and therefore did not require entities to obtain such information. Finally, builders did not fully understand the impacts that dams posed to the environment and therefore any data that were gathered may be of little scientific value. In addition, very few watersheds exist under the same conditions now as they did decades ago when they were built which could result in some difficulty recreating past conditions. The watershed may have undergone considerable permanent changes to the channel shape, gradient, floodplain, or
wetlands which could be a reason why the simulations do not precisely recreate the unobstructed watershed. Areas around watersheds have become more urbanized, stream channels have meandered, and runoff of precipitation is more controlled.

In many cases historical data post-dates dam construction and therefore gives no indication as to the condition of the river prior to construction. The most commonly used method to circumvent this problem is to use models to reproduce the types of conditions that were found prior to dam construction. The current conditions of the watershed are created and calibrated and then adjustments are made to recreate the conditions that were found at the time that is under investigation. According to the literature, this approach is acceptable in areas that have undergone sizable changes since the establishment of their impoundments (Ouyang, et al. 2011). The process of modeling required the development of model parameters and reconstruction of the conditions of the watershed as they were pre-dam. Once the physical parameters and situation have been established the model was calibrated and verified against existing water quality data. The calibrated model was then used to simulate changes in an effort to estimate the impacts that the structures have on the water quality and flow regimes of the system.

Regardless of the theme of the investigation, deliberate, careful, and thorough calibration of the water balance within the model must be accomplished. The water balance component determines all other happenings that occur within the watershed. The water balance portion of the simulation shows the amount and timing of the flow
of water in and out of the watershed and dictates the movement and amounts of nutrients, sediments, and pesticides within the watershed (Srinivasan 2005).

The comparison and analysis of the impacts that dams have on the Kalamazoo River was based on the modeling of different dam removal scenarios. The most vital part of the project was ensuring that the SWAT model could accurately represent the current conditions of the watershed. An accurate representation of the watershed ensured that when changes were made within the system a reasonable output will ensue and a valid basis for comparison exists. The methodology consisted of the application of the three different dam removal scenarios in order to explore the individual and cumulative effects that dams have on the Kalamazoo River. These three scenarios will be referred to as Dams In, Dams Out, and Up/Down. The Up/Down scenario refers to the removal of the most upstream dam first followed by the removal of the next most upstream dam. This process would be repeated until all of the dams were removed. The initial model setup follows the typical SWAT project setup as described by Srinivasan (2009).

3.3 Data Collection

Data that were collected had three purposes: 1) to approximate the physical conditions found within the watershed; 2) to serve as the basis for calibration and validation of the model; and 3) for visual comparison against the model produced data using GIS. Data compiled for the use of creating the physical environment within the Kalamazoo River watershed came from a number of sources. A Digital Elevation Model (DEM) and soil data were obtained from the Michigan Center for Geographic
Information (MiCGI). The locations of the dams and their associated information were obtained from the United States Army Corps of Engineers National Inventory of Dams website. Land Use/Land Cover (LULC) data and streamflow data came from the United States Geologic Survey (USGS). Weather data were obtained from the United States Department of Agriculture Agricultural Research Service (USDA-ARS).

Careful examination and consideration of the individual data components (i.e. climate, discharge, routing) must be carried out in order to ensure that the data accurately represents the watershed under investigation. Climate data that is used within the SWAT model should be void of excessive periods of atypical values for both temperature and precipitation (unless that is the norm for the region) but should contain the normal expected variability. Climate data must be carefully evaluated and chosen to depict the normal average conditions. Similar considerations should be made regarding data used for calibration and validation of the model. Streamflow discharge data should also adhere to the same considerations as the climatic data. Calibrations of the model and subsequent simulations have been shown to be more accurate statistically when the data that are used within the model are void of extremes. This practice is controversial because any useful model should be able to replicate and accommodate any possible conditions that may exist within the system no matter how infrequent their occurrence (Gupta, Sorooshian and Yapo 1999).

Tremendous amounts of processing are generally required to format climate data into the format that is required by SWAT. Fortunately, the climate data used for
the SWAT model came pre-processed and formatted from the USDA Agricultural Research Service (USDA-ARS). Climate data were readily corrected for completeness and formatted for input into SWAT by the USDA-ARS. The only procedure that was required to use the formatted data was to create a table with the locations of the weather stations. This process is explained in the 2005 SWAT Input/Output documentation file booklet (Neitsch, et al. 2005). The user chose to use the data for the four main counties that lie mostly within the watershed in order to eliminate extraneous data. The counties from which the data came from were Allegan, Barry, Calhoun, and Kalamazoo. The USDA-ARS evaluates the data sets for completeness and fills in missing data values with averaged data from the five nearest stations. The USDA-ARS includes metadata for the climate data which highlights the amount of data were complete and the percentage that were averaged. The metadata enhances the reliability of the data and provides a means to cross-check data values.

Streamflow (discharge) data garnered from the USGS was the most important to obtain because it is essential for calibration of the model (whereas climate data can be extrapolated from data tables within the SWAT program and is not necessarily needed to calibrate the model). The streamflow data needed to be converted from units of cubic feet per second (cfs) to millimeters (mm) as the SWAT model produces an output value as a depth in mm. The selection of the time period 1952–1980 came from three factors: the availability of streamflow data at the outlet of the watershed, continuous nitrogen and phosphorus data, and the need for a 15 year time period which is commonly used for simulations of SWAT (Murphy 2010). The nitrogen and
phosphorus data were collected continuously at the outlet of the Kalamazoo River watershed for a very small period of time (January 1978 to August 1979). Post-1979 the nutrient data were collected quarterly. The sediment data were collected regularly by the USGS starting in January 1974 to November 1984. Sediment data that were collected after 1984 were also collected quarterly. The scarcity of continuous, reliable, sediment, and nutrient data proved to be a limiting factor during the calibration and validation processes.

Table 2: Data Type and Timeframe

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Start Date</th>
<th>End Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment</td>
<td>1/1/1974</td>
<td>11/1/1984</td>
</tr>
<tr>
<td>Streamflow</td>
<td>1/1/1950</td>
<td>1/1/1980</td>
</tr>
<tr>
<td>Nutrient</td>
<td>1/1/1978</td>
<td>8/1/1979</td>
</tr>
</tbody>
</table>

3.4 SWAT Data Pre-Processing

Data that were used within the SWAT model was manipulated using ArcMap® (ESRI 2008). The Digital Elevation Model (DEM), LULC, and STATSGO soils data were imported into ArcGIS and reprojected using the “Batch Reproject” tool. The model requires that the data layers be in the same projection for precise overlay and extraction of the information contained within them. The LULC, STATSGO soils, and DEM layers were all much larger than the watershed itself and needed to be trimmed down to a more manageable size by clipping. A slightly larger than actual size rendition of the watershed boundary was created for the use of clipping out the study region. This process minimized the size of the files which allowed for quicker model simulations.
3.5 SWAT Model Setup and GIS Data Manipulation

The SWAT model setup process consisted of delineating the watershed using the Digital Elevation Model (DEM) that was obtained from the Michigan Center for Geographic Information (MiCGI). The Automatic Watershed Delineation Tool was used to combine the DEM, stream reach, and user inputs like soils and land use/land cover (LULC) to demarcate the boundary of the watershed. In order to reduce the amount of area that the SWAT had to perform calculations to, the watershed area was masked out with a manually drawn and created mask grid using ArcMap (ESRI 2008). This process was completed by importing a correctly projected grid file which shows the watershed boundary into ArcSWAT and then following the boundary of the watershed. It was important to create a file which has a slightly larger area than the watershed itself in order to prevent improper routing of the water within the system. After masking out the undesired areas surrounding the watershed, the model requires the watershed stream network to either be estimated based on a user defined threshold area or suggests that a stream network reach file is imported from the National Hydrography Dataset. The stream network was imported in order to produce a more accurate representation of the locations of the impoundments. The next step was to provide the information for the creation of the HRUs. This process subdivides the sub-watersheds into the smaller HRU units for the purpose of routing the water through the watershed. Based on the size of the watershed the model suggested a minimum area of 2072 hectares per HRU. Through trial and error it was determined that 2250 hectares was the ideal minimum size to accurately replicate the locations of
the dams. This is important because the SWAT program will only place the dams at the outlet of the HRU and these locations do not coincide with the actual placement of the structures.

The next step in the setup of the model is selection of the watershed inlet (if applicable) and outlet. The inlets represent any point source (streamflow, sediment, nutrients, or pesticides) that directly contribute to the study area from areas upstream and the outlet is the location of the most downstream point of the watershed. After the selection of the watershed outlet the location of the reservoirs/dams were added to the model. The reservoirs are automatically placed at the junction between two separate but connected sub-watersheds. Some trial and error went into defining the minimum area of the sub-watersheds. Changes to the minimum size allowable for the creation of these sub-watersheds allowed for a more accurate placement of the dams and their reservoirs within the watershed.

Following the watershed delineation land use, slope, and soil definitions were specified. This process involved defining the names and properties of the data within the model. The Hydraulic Response Unit (HRU) menu allowed the user to specify the soils, land use, and slope themes that are used to separate the watershed into sub-watersheds which dictates the movement of water through the system. These parameters were reclassified and resulted in the following informational data tables (Tables 3-5).
Table 3: Land Use Classification within SWAT

<table>
<thead>
<tr>
<th>LANDUSE:</th>
<th>Abbrev.</th>
<th>Area [ha]</th>
<th>Area [acres]</th>
<th>% Wat. Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential-Medium Density</td>
<td>URMD</td>
<td>18085</td>
<td>44688.9393</td>
<td>4.36</td>
</tr>
<tr>
<td>Commercial</td>
<td>UCOM</td>
<td>4229</td>
<td>10450.0705</td>
<td>1.02</td>
</tr>
<tr>
<td>Industrial</td>
<td>UIDU</td>
<td>1819</td>
<td>4494.84</td>
<td>0.44</td>
</tr>
<tr>
<td>Transportation</td>
<td>UTRN</td>
<td>3127</td>
<td>7726.9734</td>
<td>0.75</td>
</tr>
<tr>
<td>Agricultural Land-Generic</td>
<td>AGRL</td>
<td>300326</td>
<td>742120.5623</td>
<td>72.46</td>
</tr>
<tr>
<td>Orchard</td>
<td>ORCD</td>
<td>426</td>
<td>1052.6673</td>
<td>0.1</td>
</tr>
<tr>
<td>Forest-Deciduous</td>
<td>FRSD</td>
<td>56691</td>
<td>140086.2956</td>
<td>13.68</td>
</tr>
<tr>
<td>Forest-Evergreen</td>
<td>FRSE</td>
<td>37</td>
<td>91.4289</td>
<td>0.01</td>
</tr>
<tr>
<td>Forest-Mixed</td>
<td>FRST</td>
<td>2285</td>
<td>5646.3493</td>
<td>0.55</td>
</tr>
<tr>
<td>Water</td>
<td>WATR</td>
<td>6970</td>
<td>17223.2185</td>
<td>1.68</td>
</tr>
<tr>
<td>Wetlands-Forested</td>
<td>WETF</td>
<td>12630</td>
<td>31209.3615</td>
<td>3.05</td>
</tr>
<tr>
<td>Wetlands-Non-Forested</td>
<td>WETN</td>
<td>7506</td>
<td>18547.7013</td>
<td>1.81</td>
</tr>
<tr>
<td>Range-Grasses</td>
<td>RNGE</td>
<td>313</td>
<td>773.4387</td>
<td>0.08</td>
</tr>
</tbody>
</table>

The USGS Land Use/Land Cover dataset was reclassified by the SWAT program which yielded Table 3. The majority of the land within the Kalamazoo River watershed falls within four main classes: Agricultural Land-Generic (72.46%), Deciduous Forest (13.68%), Medium Density Residential (4.36%), and Forested Wetlands (3.05%) respectively.

The soil orders were imported into and reclassified within the SWAT model. There were 20 distinct soil orders classified by the model (one of the classes – MIW is water) based on the land cover classifications that are provided with the data. A breakdown of the results of the reclassification process is shown below in Table 4. The distribution of the individual soil orders by name and their soil codes can be seen in Figure 4.
Table 4: Soil Order Codes by Area

<table>
<thead>
<tr>
<th>Soil Code</th>
<th>Area [ha]</th>
<th>Area [acres]</th>
<th>% Wat. Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>MI006 Silty Loam</td>
<td>1421</td>
<td>3511.36</td>
<td>0.34</td>
</tr>
<tr>
<td>MI011 Sandy Loam</td>
<td>42141</td>
<td>104132.51</td>
<td>10.17</td>
</tr>
<tr>
<td>MI014 Loamy Sand</td>
<td>14809</td>
<td>36593.77</td>
<td>3.57</td>
</tr>
<tr>
<td>MI022 Muck</td>
<td>7630</td>
<td>18854.11</td>
<td>1.84</td>
</tr>
<tr>
<td>MI023 Muck</td>
<td>2580</td>
<td>6375.30</td>
<td>0.62</td>
</tr>
<tr>
<td>MI024 Sand</td>
<td>9559</td>
<td>23620.76</td>
<td>2.31</td>
</tr>
<tr>
<td>MI034 Sandy Loam</td>
<td>49840</td>
<td>123157.13</td>
<td>12.03</td>
</tr>
<tr>
<td>MI035 Loam</td>
<td>13195</td>
<td>32605.50</td>
<td>3.18</td>
</tr>
<tr>
<td>MI036 Loam</td>
<td>27335</td>
<td>67546.15</td>
<td>6.6</td>
</tr>
<tr>
<td>MI041 Loam</td>
<td>5040</td>
<td>12454.09</td>
<td>1.22</td>
</tr>
<tr>
<td>MI043 Gravel/Sand</td>
<td>10482</td>
<td>25901.54</td>
<td>2.53</td>
</tr>
<tr>
<td>MI045 Sandy Loam</td>
<td>91084</td>
<td>225073.11</td>
<td>21.98</td>
</tr>
<tr>
<td>MI046 Sand</td>
<td>43167</td>
<td>106667.81</td>
<td>10.42</td>
</tr>
<tr>
<td>MI047 Sandy Loam</td>
<td>15673</td>
<td>38728.76</td>
<td>3.78</td>
</tr>
<tr>
<td>MI048 Loamy Sand</td>
<td>36282</td>
<td>89654.63</td>
<td>8.75</td>
</tr>
<tr>
<td>MI058 Silty Clay</td>
<td>348</td>
<td>859.92</td>
<td>0.08</td>
</tr>
<tr>
<td>MI082 Sandy Loam</td>
<td>5972</td>
<td>14757.11</td>
<td>1.44</td>
</tr>
<tr>
<td>MI083 Mucky Sand</td>
<td>9659</td>
<td>23867.87</td>
<td>2.33</td>
</tr>
<tr>
<td>MI084 Clay Loam</td>
<td>4619</td>
<td>11413.78</td>
<td>1.11</td>
</tr>
<tr>
<td>MI091 Sandy Loam</td>
<td>21876</td>
<td>54056.68</td>
<td>5.28</td>
</tr>
<tr>
<td>MIW Water</td>
<td>1732</td>
<td>4279.85</td>
<td>0.42</td>
</tr>
</tbody>
</table>

The user defined slope classification followed the work done by Bosch (2008) and Neitsch, et al. (2005) which suggest that creating more than three classification classes may result in the creation of circular arguments within the model and thus three slope classification classes were used (Table 5).

Table 5: Slope Classifications within SWAT

<table>
<thead>
<tr>
<th>% SLOPE:</th>
<th>Area [ha]</th>
<th>Area [acres]</th>
<th>% Wat. Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-4</td>
<td>395097</td>
<td>976304.442</td>
<td>95.33</td>
</tr>
<tr>
<td>4-8</td>
<td>18811</td>
<td>46482.9216</td>
<td>4.54</td>
</tr>
<tr>
<td>8-9999</td>
<td>536</td>
<td>1324.4828</td>
<td>0.13</td>
</tr>
</tbody>
</table>
Once the reclassification was completed the layers were then overlain and defined based on a user defined minimum percentage. This process creates the hydrologic response units which form the base for all the happenings within the watershed. The user defined the minimum level to be 10% for soils, slope, and land use. This resulted in the creation of 97 HRUs within the boundary of the main watershed.

Creation of the database input tables which hold the weather, soil, water use, groundwater, channel, management, and configuration files was the final step before
beginning the calibration process. The weather data files and a user created locations table needed to be placed in an easily accessible file folder within the SWAT main directory. This process is described in the SWAT Users Guide located in the SWAT project toolbar. Upon the successful generation of the databases the calibration and validation processes were started.

3.6 Calibration and Validation of the SWAT Model

Calibration of the SWAT model was preceded by performing a sensitivity analysis on the parameters that control the movement of water, nutrients, and sediment. The sensitivity analysis conducts a series of trial model simulations to determine which input parameters have the largest effect on the model output (Neitsch, et al. 2005). Within the SWAT model there are two different methods of sensitivity analysis, they are called the Sources of UNcertainty GLobal Assessment using Split SamplES (SUNGLASSES) method and the PARAMeter SOLutions (PARASOL) method. The PARASOL method was the selected sensitivity analysis used in this study.

Results of calibration and validation modeling was assessed in terms of the fit of models’ produced values to known water quality and quantity data based on accepted statistical methods such as Pearson’s correlation coefficient, coefficient of determination, Nash-Sutcliffe efficiency (NSE), Root Mean Square Error (RMSE) and Percent Bias (PBIAS). Hydrographs and probability curves based on the streamflow aided in visualizing the models performance.
The calibration of the model took place from January 1, 1978 to December 31, 1978. The timeframe for the validation period was January 1, 1979 to December 31, 1980. The calibration and validation of the model follows a logical and strict procedure which must be adhered to in order to ensure that the model will produce a viable output. A manual calibration of the model was performed after a sensitivity analysis identified the changeworthy variables for streamflow, sediment, and both nutrients (nitrogen and phosphorus). According to the SWAT calibration techniques manual, the hydrology of the system must be calibrated first and then the sediment and water quality (nutrient) parameters can be calibrated (Srinivasan 2009). The user followed the standard procedure for calibrating the hydrology of the model. The initial step was to correct the water balance of the system first to ensure that all of the water in the system is accounted for. This process made sure that the amount of water that has been created by the model is equivalent to the amounts found in the precipitation and streamflow data. This step was accomplished by adjusting the sensitive parameters to correct the annual totals and then repeating the process for the monthly totals. The water balance procedure ensures that the amount of water in the system for the year is correct and the timing of the water cycling accurately represents the real world conditions (Srinivasan 2009). The results of the calibration simulations were initially assessed for accuracy by looking at the mean and standard deviation of the simulated and measured data. A better measure of the accuracy of the model produced values were obtained by calculating the regression coefficient, coefficient of determination ($R^2$), Pearson’s correlation coefficient ($r$), and Nash-Sutcliffe
efficiency (NSE) values – a brief description of these statistics is found in the results section starting at section 3.8. Following the procedure in this manner also helps the user cross-check the adjustments made to the input parameters and protects against the incorrect adjustment of parameters. In addition to these statistical evaluations hydrographs, time-series plots, and frequency duration curves can be used to verify the accuracy of the modeled data (Srinivasan 2009).

The sensitivity analysis revealed which of the variables contributed the most to the overall characteristics found within the watershed. The sensitivity analysis step can be omitted but it can significantly reduce the amount of trial and error associated with the manual calibration process. The PARASOL method ranks the variables in order of their sensitivity to change. The sensitivity analysis showed that the most sensitive values related to streamflow were: CN_2, Alpha_BF, EPCO, ESCO, Sol_Awc, Rchrg_dp, Sol_K, and Sol_Z.

CN_2 represents the Curve Number; a hydrologic rating of a soil group. The CN_2 estimates the amount of surface runoff of a HRU based on its land use classification, soil type (and their characteristics), and the percentage of the land cover to determine the amount of precipitation that comes from overland runoff and contributes directly to the streamflow. The CN_2 value can only be adjusted by +/- 20 percent of the value provided by SWAT.

The Alpha_BF is the baseflow recession constant and Rchrg_dp is the deep aquifer percolation fraction. Rchrg_dp depicts the groundwater aquifer height. Adjusting the Rchrg_dp value raises and lowers the height of the water table.
Increasing the height of the water table will result in higher streamflow due to increased lateral movement of water within the aquifer. The Alpha_BF and Rcharg_dp are used to govern subsurface water response.

EPCO is the Plant uptake compensation factor. The EPCO value is another means of balancing the water budget of the model. EPCO values range from 0.01 to 1. An EPCO value of 1 allows more of the water to be taken up by plants whereas an EPCO value closer to 0.01 allows less water to be taken up by plants.

The ESCO value is the Soil Evaporation Compensation Coefficient. ESCO is a percentage of the water held in the soil that is lost to evaporation. The ESCO value can be adjusted in a range from 0 to 1. A value of 0 would represent no loss of soil moisture from evaporation and a value of 1 would represent the maximum loss of soil moisture. The ESCO value is related to the texture of the soil and its clay content. The particle size (and thus porosity) of the type of soil provides a basis for the amount of water needed for saturation, wilting, and field capacity. Field capacity is the maximum amount of water that a soil of rock can hold, as by capillary action, before the water is drawn away by gravity (Dictionary.com 2012).

Sol_Z is the depth from the soil surface to the bottom layer (in millimeters). The Sol_Z value is the thickness of the soil profile in the HRU. This value dictates the movement of water based on the soil temperature as a function of the depth. Changes to the Sol_Z value will change the timing of subsurface flow within the aquifer.
Sol_K represents the saturated hydraulic conductivity of the first layer (mm/hr). Like the Sol_Z value, Sol_K controls the subsurface movement of water into the river. The Sol_K, CN_2, and Sol_Z variables are used to calculate the amount of water that enters/leaves the soil. The water that does infiltrate into the soil becomes surface runoff.

A more in-depth description of all of the parameters and their ranges can be found in the SWAT Input/Output documentation file booklet (Neitsch, et al. 2005). It would not be beneficial or relevant to discuss all of the associated equations and sub-equations that comprise these parameters. The documentation file booklet succinctly describes the processes, equations, and parameters that the model uses under different scenarios.

It is suggested that a sensitivity analysis be performed for sediment, nitrogen, and phosphorus as well. The SWAT users guide states that the sensitivity analysis and calibration for sediment must be performed first. The nutrient sensitivity analysis can only be done after the streamflow and sediment have been done. The most sensitive variables related to sediment were found to be: USLE_P, Ch_Erod, Ch_Cov, Spcon, and Spexp.

The Ch_Erod variable represents the channel erodibility factor (it has the unit: cm/hr/Pa). Ch_Erod is a coefficient and is represented by a number between 0 and 1. Ch_Erod is used to adjust the amount of sediment that is discharged as a result of channel erosion.
USLE_P is the Universal Soil Loss Equation support practice factor. The USLE_P value employs agricultural land use practices such as filter stripping and tilling practices to induce or restrict the movement of sediment into the stream channel from overland flow. USLE_P is made up of several components which each have their own level of adjustability.

Ch_Cov is the channel cover factor and is defined as a ratio of degradation from the channel with a specific type and amount of vegetative cover versus the same channel without a vegetative cover. This value affects the stream discharge inversely; as the amount of vegetation increases the stream discharge decreases. Unfortunately, the results of the sensitivity analysis for these variables had no bearing on the outcome of the model because the overall water balance could not be validated. An incorrect water balance would produce sediment and nutrient values that do not correspond to real world conditions.

Spcon is a coefficient in the sediment transport equation and Spexp is an exponent in the sediment transport equation. These components are associated with the downcutting and widening of the stream channel. Typical situations and models use the same channel dimensions during the duration of a simulation but with SWAT the channel dimensions are permitted to adjust following regime changes.

Once again, a more complete description of these variables can be found in the Input/Output documentation file (Neitsch, et al. 2005). Changes made to the sediment variables during the calibration process proved to be fruitless. The variables that control the movement within the system were all changed systematically and
were incapable of reproducing the values shown by the observed data. The user evaluated the impacts of each variable by changing its coefficient through the range of minimum and maximum allowable values. The values listed under the cumulative change heading show the mathematical operation and numerical value that each variable was adjusted by during the most successful calibration. For instance, if the initial value for Rchrg_Dp was 40; the model was shown to be the most accurate when 10 was added to the initial value of 40 – resulting in the recharge depth being 50. The manual calibration method allows the parameters in the model to be adjusted by adding, subtracting, multiplying, or dividing the SWAT provided value. Adjustments to the parameters can only be made for a fixed range. The model produces error messages when one of the threshold values has been exceeded. The Changes that were made to all of the variables during the manual calibration are shown in Table 6.

Table 6: Changes Made During Manual Calibration

<table>
<thead>
<tr>
<th>Variable Code</th>
<th>Cumulative Change</th>
<th>SWAT Default Value</th>
<th>SWAT Accepted Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rchrg_Dp</td>
<td>(+) 10 %</td>
<td>0.05</td>
<td>+/- 25 %</td>
</tr>
<tr>
<td>Sol_K</td>
<td>(x) 26.22</td>
<td>10</td>
<td>8 - 500</td>
</tr>
<tr>
<td>CN_2</td>
<td>(x) 0.85</td>
<td>55</td>
<td>10 - 90</td>
</tr>
<tr>
<td>Sol_Awc</td>
<td>(x) 2.09 %</td>
<td>0.1</td>
<td>0.10 - 0.20</td>
</tr>
</tbody>
</table>

Streamflow (discharge) was the only variable that was capable of being accurately calibrated. The model produced values for sediment and nutrients were not in accordance with the obtained values. In order for the values to be changed enough to be able to replicate the observed data, the model parameters had to be changed in
excess of the maximum possible values. This would result in the unrealistic portrayal of the conditions found within the watershed. Streamflow values were able to be satisfactorily calibrated but not validated for. Table 6 and Figure 5 compare the simulated (calibrated and validated values) and observed flow for the Kalamazoo River. The values listed under the USGS heading are real-world collected data values for streamflow provided by the USGS. The values listed under the Calibration heading were produced by SWAT based on the changes made as a result of the sensitivity analysis.

The outputs from SWAT during the calibration and validation phases and the USGS streamflow data in Table 7 are described in millimeters. The USGS streamflow data needed to be converted from cubic feet per second (cfs) to depth per month in millimeters. The conversion was completed using Equation 1. The area measurement of the watershed was provided by SWAT as a part of the watershed delineation process. SWAT determined that the delineated watershed area was approximately 4,144,440,265 square meters (44,610,383,742 square feet). The SWAT produced estimation of streamflow must be within +/- 10% of the USGS values in order to be deemed acceptable for use.

Equation 1: Conversion of USGS Streamflow to Millimeters

\[
USGS \ (in \ mm) = \frac{(USGS \ in \ cfs \times 86,400 \times days \ in \ the \ month \times 304.8 \ mm)}{watershed \ area \ in \ ft^2}
\]
Table 7: Calibration and Validation Values for Streamflow

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>14.73</td>
<td>13.28</td>
<td>12.32</td>
</tr>
<tr>
<td>Feb</td>
<td>17.33</td>
<td>18.38</td>
<td>17.9</td>
</tr>
<tr>
<td>Mar</td>
<td>28.77</td>
<td>23.91</td>
<td>25.91</td>
</tr>
<tr>
<td>Apr</td>
<td>28.61</td>
<td>21.57</td>
<td>21.63</td>
</tr>
<tr>
<td>May</td>
<td>22.59</td>
<td>16.03</td>
<td>15.64</td>
</tr>
<tr>
<td>Jun</td>
<td>16.38</td>
<td>20.27</td>
<td>21.76</td>
</tr>
<tr>
<td>Jul</td>
<td>13.74</td>
<td>11.95</td>
<td>12.92</td>
</tr>
<tr>
<td>Aug</td>
<td>10.60</td>
<td>10.97</td>
<td>12.11</td>
</tr>
<tr>
<td>Sep</td>
<td>13.02</td>
<td>13.78</td>
<td>13.42</td>
</tr>
<tr>
<td>Oct</td>
<td>11.92</td>
<td>11.07</td>
<td>11.01</td>
</tr>
<tr>
<td>Nov</td>
<td>12.28</td>
<td>13.84</td>
<td>13.66</td>
</tr>
<tr>
<td>Dec</td>
<td>17.71</td>
<td>16.08</td>
<td>16.44</td>
</tr>
<tr>
<td>Σ (yearly)</td>
<td>207.67</td>
<td>191.13</td>
<td>194.72</td>
</tr>
</tbody>
</table>

92.04%  93.76%
3.7 Scenario Development

Unfortunately the model was unable to be successfully validated for the period in question. A systematic approach was employed to assess the reasons why the model could not reproduce values similar to the observed data. The streamflow results failed to reveal any specific link between the coefficients used to express the physical parameters and the model outputs. This indicated that even with significant changes to the coefficients the values had either reached their maximum possible values or were simply incapable of reflecting the additional change.
The second scenario that was to be created consisted of all of the current physical condition data from the “Dams In” scenario with the only difference being the removal of the three main dams within the EPAs area of concern (AOC). This “Dams Out” scenario was to be compared to the “Dams In” scenario in order to estimate the cumulative impacts of the dams within the area of concern. The next step was to evaluate each dam’s impact on the watershed by selectively removing individual impoundments. The removal of certain structures was to be used to identify the individual impacts of each structure and test the hypothesis that impoundments create conditions that lead to the sequestration of nutrients.

The third scenario was the “Up/Down” scenario. The goal of the “Up/Down” scenario was to evaluate the claim made by Doyle, et al. (2005) that the most upstream dams have a greater impact on water quality than do more downstream dams. The removal of dams that are further upstream first, in theory, could lessen the nutrient and sediment loading from the streambed by deterring the resuspension of previously settled sediment. The attached PCBs and sequestered nutrients would also be impacted through this mechanism.

3.8 Description of Statistics Used in the Analysis

3.8.1 Standard Deviation

One of the most common statistical measurements used to evaluate data or values produced by a model is the standard deviation calculation. The standard deviation of a dataset is a measure of the dispersion of a set of data from its mean. There are no official guidelines for the SWAT model regarding acceptable values for
standard deviation. However, since standard deviation describes the dispersion of data from its mean a smaller value is optimal.

3.8.2 Pearson’s Correlation Coefficient (r) and Coefficient of Determination (R²)

The Pearson’s correlation coefficient and coefficient of determination are statistics which describe the co-linearity of simulated data to observed data (Moriasi, et al. 2007). The Pearson’s value has a range from -1 to 1 with 0 representing no linear relationship, -1 representing a strong negative linear relationship, and 1 representing a strong positive linear relationship.

The R² value ranges from 0 to 1 and is often used to describe the proportion of the variance in measured data explained by the mode (Moriasi, et al. 2007). R² values describe the variability that is accounted for by a regression model. For SWAT simulations, Santhi, et al. (2001) cites that values which are > 0.5 are considered acceptable.

One of the drawbacks of using R² and r are the inability of these statistics to adjust for proportional value changes. For example, the increase of simulation values by exactly the same amount from the previous measurement (e.g. all values increased by a value of 5) will yield the same R² and r values as was seen in the first simulation. For this reason, the Nash-Sutcliffe efficiency is seen as being a more accurate representation of the acceptability of modeled data.

3.8.3 Nash-Sutcliffe Efficiency (NSE)

Like the Pearson’s correlation coefficient and the coefficient of determination the Nash-Sutcliffe efficiency (NSE) describes the co-linearity of the simulated data to
the observed data. However, the NSE is a normalized statistic which uses the variance of the observed and simulated data and compares that to the measured data variance of the observed data and its mean (Nash and Sutcliffe 1970). The NSE is calculated by using the equation below (Equation 2). The variables in the following equations represent the following data: $Y^{obs}$ is the observed streamflow data, $Y^{sim}$ is the SWAT produced values, $Y^{mean}$ represents the mean of the observed data and $STDEV_{obs}$ is the standard deviation of the observed USGS data.

\[
NSE = 1 - \left[ \frac{\sum_{i=1}^{n} (Y^{obs}_i - Y^{sim}_i)^2}{\sum_{i=1}^{n} (Y^{obs}_i - Y^{mean})^2} \right]
\]

The result of the NSE computation indicates how well the simulated data fits a 1:1 line versus the observed data (Moriasi, et al. 2007). The NSE values fall within a range of negative infinity (- $\infty$) to 1, with values closer to 1 describing a perfect colinearity of the simulated data to the observed data. Moriasi, et al. (2007) determined that the acceptable values for NSE are between 0 and 1. NSE values that are equal to or fall below zero indicate that the mean of the observed values is a better predictor than the values produced by the simulation (Moriasi, et al. 2007). The guidelines put forth by Moriasi, et al. (2007) set the NSE values for acceptable SWAT simulations at a value greater than (> ) 0.5.
3.8.4 Root Mean Square Error (RMSE), Mean Square Error (MSE), and RMSE-Observations Standard Deviation Ratio (RSR)

The Root Mean Square Error, Mean Square Error, and RMSE-Observations Standard Deviation Ratio are error indices which describe the amount of error associated with the simulated data. Singh, Knapp, and Demissie (2004) via Moriasi, et al. (2007) suggest that the RMSE value be less than half the standard deviation of the measured data in order to be acceptable. Low values of RMSE and MSE are preferred because values of zero suggests that there is no error between the simulated data and the observed data (Santhi, et al. 2001).

The RMSE-Observations Standard Deviation Ratio (RSR) is another error index developed by Singh, Knapp, and Demissie (2004) which standardizes the RMSE and uses an error index to allow for the comparison and analysis of different variables whose data values may vary greatly. The RSR value ranges from 0 to a large positive value with a value of 0 representing no residual variation of the simulated data (Santhi, et al. 2001). The formulas for RMSE (Equation 3), MSE (Equation 4), and RSR (Equation 5) are shown below:

**Equation 3: Root Mean Square Error (RMSE)**

$$ RMSE = \sqrt{\frac{\sum_{i=1}^{n} (y_{i}^{obs} - y_{i}^{sim})^2}{n}} $$

**Equation 4: Mean Square Error (MSE)**

$$ MSE = \frac{\sum_{i=1}^{n} (y_{i}^{obs} - y_{i}^{sim})^2}{n} $$
Equation 5: RMSE- Observations Standard Deviation Ratio (RSR)

\[
RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[ \sqrt{\sum_{i=1}^{n} (Y_{obs} - Y_{sim})^2} \right]}{\left[ \sqrt{\sum_{i=1}^{n} (Y_{obs} - Y_{mean})^2} \right]}
\]

3.8.5 Percent Bias (PBIAS)

The Percent Bias (PBIAS) equation calculates the average tendency of model simulated data in comparison to the observed data shown as a percent (Gupta, Sorooshian and Yapo 1999). The PBIAS value will suggest if the simulated data values are generally higher or lower than the observed data. The ideal PBIAS value is 0 – which would mean that there is no over or under estimation shown by the simulated values. A positive PBIAS value reveals an underestimation of model produced values and a negative PBIAS value represents the opposite situation. The PBIAS statistic is calculated using Equation 6.

Equation 6: Percent Bias (PBIAS)

\[
PBIAS = \left[ \frac{\sum_{i=1}^{n} (Y_{i}^{obs} - Y_{i}^{sim})}{\sum_{i=1}^{n} (Y_{i}^{obs})} \right] \times (100)
\]
CHAPTER 4

RESULTS

4.1 Summary of the Results

The streamflow results from the “Dams In” simulation were the only ones that were found to be acceptable by the statistical analysis and thus were the only values that are described. The dam removal scenarios were unable to be performed because the results of the statistical analysis dictated that the model was incapable of accurately recreating the watershed. A table of the pertinent data and statistics for each of the phases of the model (calibration and validation) from the “Dams In” scenario is placed after the description of the results. The values produced by the simulations are deemed acceptable if the model produced values fall within the ranges of acceptable values allowed by the statistical analysis’ described in Chapter 3.

4.2 Scenario 1 – “Dams In” (Current Baseline Condition)

4.2.1 Streamflow Results

The model produced values for the calibration phase that were statistically acceptable according to the guidelines set by Moriasi, et al. (2007). The calibration phase of the model could account for 191.13 millimeters (mm) of the 207.67 mm of actual discharge reported by the USGS. This corresponded to a Pearson’s correlation coefficient value and a NSE value of approximately 0.831 and 0.652. However, during the validation phase this accuracy was not repeated. The accuracy of the model
fell to 0.460 and -5.314 for the same measurements during the first attempt at validation. After recalibrating the model the values for both the Pearson’s and NSE fell within the acceptable ranges but were once again deemed unsatisfactory upon completion of the second validation according to the guidelines set by Moriasi, et al. (2007). The highest statistical values that were produced by the model during the validation phase were 0.804 for Pearson’s and 0.367 for the NSE. The statistics and model outputs resulting from the calibration and validation of the “Dams In” scenario can be seen in Table 8 and Figure 6.

Table 8: Results of the Calibration and Validation Phases – “Dams In”

<table>
<thead>
<tr>
<th>Stage</th>
<th>PBIAS</th>
<th>RMSE</th>
<th>St. Dev.</th>
<th>Pearson’s</th>
<th>NSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration of Streamflow 1</td>
<td>2.638</td>
<td>12.158</td>
<td>5.413</td>
<td>0.831</td>
<td>0.652</td>
</tr>
<tr>
<td>Calibration of Streamflow 2</td>
<td>3.37</td>
<td>12.015</td>
<td>5.263</td>
<td>0.863</td>
<td>0.661</td>
</tr>
<tr>
<td>Validation of Streamflow 1</td>
<td>2.441</td>
<td>17.606</td>
<td>5.916</td>
<td>0.749</td>
<td>0.271</td>
</tr>
<tr>
<td>Validation of Streamflow 2</td>
<td>1.988</td>
<td>16.795</td>
<td>6.010</td>
<td>0.769</td>
<td>0.337</td>
</tr>
</tbody>
</table>

The results look to be skewed due to the unusual pattern of seasonal discharge during the validation phase. The skewed-ness of the data can be seen in Figure 6 as the line representing the USGS discharge differs slightly in terms of the timing of the discharge as compared to the discharge found during the calibration phase. The model consistently predicted an uncharacteristic spike in discharge during the month of June which simply did not exist. In addition, the model generally produced lower than expected values for the months of March and April.
Changes to the model coefficients that dictated the timing and amount of snowmelt in the spring did not remedy these issues. These outcomes were not expected based on the values found within the observed data or the coefficients that represented the real world conditions within the model.

4.2.2 Sediment and Nutrient Results

As was stated before, the statistics revealed that the streamflow values that were produced by the model could not be validated. This meant that the nutrient data could not be calibrated or validated correctly because the amount and timing of water in the system would skew the movement and release of sediment and nutrients. The
water balance of the system must be correct before moving on to calibration and validation of the sediment and nutrients.
CONCLUSION

5.1 Overall Impact/Summary

In spite of the inability of the model to accurately reproduce the volume of water, sediment and nutrients to substantiate the research aims, the modeling efforts did allow for the identification of the need for quality water data for the Kalamazoo River watershed. This is valuable because it identified the critical need for more accurate record keeping and collection of the water quality data within the Kalamazoo River watershed. The lack of sufficient periods of time for which water quality data can be had should be of concern to the decision makers of the watershed. In order to use models like SWAT as a tool to manage watersheds, routinely collected quality data must be available and accessible. The models ineffectiveness could be a result of several different factors. First, the parameters that were to be changed as suggested by the sensitivity analysis actually were not the most responsive due to the lack of input data. Second, because of the lack of continuous data the timeframe of the data for the validation period was far shorter than the calibration period.

The SWAT model was not capable of accurately reproducing the Kalamazoo River watershed in order to simulate the impacts that dams have on the water quantity and quality of the river. The SWAT model could not be used to quantify the impacts that the several dams within the AOC have on the watershed. The inability of the dam removal scenarios to be completed makes it uncertain if the watershed would benefit
from the removal of the dams. However, the proximity of the output of the model
does suggest that if there were more, higher quality data available that the model
would be capable of producing a reasonable approximation of the conditions found in
the watershed. Perhaps employing the use of the other sensitivity analysis (such as the
SUNGLASSES method) as a cross-check may have revealed similarities or
differences in the importance levels of the variables. The outcome with the current
dataset would not have changed because the user used the entire range of acceptable
values for each variable.

There have been minor successes in using SWAT to estimate sediment and
nutrients following dam removal. Bosch (2008) and (Safferman, et al. 2007) both
cases employed the use of primary nutrient and sediment data rather than the
secondary data that was used in my study.

5.2 Implications of the Results

The inability of SWAT to accurately reproduce the conditions found within
the watershed in order to come up with best management practices for dam removals
should not deter further research. SWAT along with GIS were capable of housing and
organizing data which offered a seamless integration of information from different
sources. The functionality of these programs should not be questioned however; the
processes that take place within this particular watershed should be better identified
through field studies prior to undertaking any form of modeling. The most successful
modeling results that have taken place within the watershed have come about from
the use of primary gathered data (see Bosch 2008). The collection of primary baseline
water quality data prior to the use of SWAT would likely enhance the ability of the
model to accurately reproduce the conditions found within the watershed. More
research should be aimed at identifying the ideal length and volumes of data required
to undertake a study such as this one.

5.3 Limitations of Procedure and Data

Data continuity was a very difficult problem to overcome. In years in which
the government had contributed significant amounts of money to environmental
agencies there was a distinct difference in data gathering. Lack of funding during
certain years likely led to less frequent data collection as well as changes to less
expensive data gathering methods. These changes may have impacted the data
enough to cause the model to break down when trying to reproduce the water quality
characteristics. Because the water samples were not taken at the site of the dams
significant improvements in accuracy of the SWAT model may have been seen if the
data that were used were collected at the outflow of the last impoundment rather than
at the mouth of the river.

Several data parameters had multiple samples taken on the same date. Some
of these data differed from one another by more than 10 %. In cases where data were
duplicated for the same date an average was calculated and used to replace the value.
This procedure likely led to increased error in the input data but it cannot be known
with certainty. Differences in the methods used for collecting the water quality data as
well as differences in the processing of water quality samples may also have
significantly impacted the outcome of the model.
5.4 Improvements and Considerations for Further Research

Several changes could be made in order to improve the ability of the SWAT model to be used for estimating the impacts of dams. As suggested by agricultural studies the model could be improved by calibrating by smaller sub-watersheds as opposed to one large watershed (Murphy, 2010, Kliment, Kadlec and Langhammer, 2008, Geying, Ge and Feng, 2006). This would allow for problem areas to be discovered and resolved independently of the rest of the watershed. This step would increase the amount of work needed to construct a whole working watershed and would depend greatly on the availability of data in the sub-watershed components.

The limited options for parameter changes to reservoirs have been cited by Murphy (2010). Murphy’s research showed that several pieces of the model that dealt with these reservoirs were inaccurate and likely reduced the ability of the model to recreate reservoired watersheds.

The lack of continuous nutrient and sediment data was detrimental to the overall outcome of the project. At first glance, data were plentiful and easily accessible but later it was realized that there were several gaps in the dates of the data which only allowed for a brief validation and calibration period. The time frame was sufficient enough to conduct an accurate calibration however the data available for the validation phase was less than ideal according to typical modeling practices. Likewise, data were gathered and analyzed by different methods (this should be expected over long periods of time since technology improves and methods become
refined). This led to the elimination of spans of data due to the uncertainty associated with its accuracy.

Bosch (2008) cites that changes in the presence and placement of reservoirs in his modeling of the Huron and Raisin Rivers in southeast Michigan had a substantial impact on the size and timing of annual nutrient loading. It is not clear whether the placement of impoundments at the terminal end of the sub-watersheds by the SWAT model is included in that assessment. More exploration and planning on this topic could alleviate some of the inaccuracy and timing problems. In addition, the creation of a SWAT data clearinghouse would allow for the standardization of data and procedures for undertaking a SWAT project. This SWAT data clearinghouse could increase the likelihood that data related problems and difficulties could be identified and corrected thus facilitating the SWAT models use for projects such as this one.
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