RIPARIAN VEGETATION RESPONSE TO STREAMFLOW ALTERATION DUE TO DAM CONSTRUCTION IN A RANGE OF RIVERS ACROSS THE UNITED STATES

by

DINUKE SASHI NANAYAKKARA MUNASINGHE

SAGY COHEN, COMMITTEE CHAIR
EBEN BROADBENT
BARBARA RASAIAH

A THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Geography
in the Graduate School of
The University of Alabama

TUSCALOOSA, ALABAMA

2017

ABSTRACT

Hydrologic variability plays a major role in structuring the riparian vegetation within river ecosystems. This study evaluates the spatial and temporal response of riparian vegetation to altered flow regimes below 16 river dams across the contiguous United States using a combination of a holistic Environmental Flow Assessment approach and satellite remote sensing.

River flows were characterized using thirty-three (33) different Indicators of Hydrologic Alteration (IHA) using the Range of Variability Approach (RVA). The alterations of riverflows were determined for post-dam scenarios comparing between the pre-dam and post-dam IHAs. Of the 16 locations assessed, 2 showed low levels, 11 moderate and 3 high levels of alteration.

Change detection of riparian vegetation revealed an increase at majority of the sites (10 of the 16) **immediately after** the construction of the dam. Also, in a majority of the locations a decrease (10 of the 16) in vegetation was observed at the **1 year post-dam completion** mark. Analyses show that vegetation change effects due to flow regime alterations below smaller dams occurred at shorter time spans (1-year post-completion) than larger dams (5-year post completion). It is inferred that categorizing dams based on capacity was successful in understanding effects on the vegetation extents better. In addition to the in-stream flow paradigm, regional climate and geomorphology are also identified as driving factors of riparian vegetation regulation. The need for a multi-factor model that drives annual changes in riparian zones is recognized to make better-informed decisions on sustainable dam operations.

DEDICATION

To my loving parents…

LIST OF ABBREVIATIONS AND SYMBOLS

WCD	World Commission on Dams
TM	Thematic Mapper
ETM+	Enhanced Thematic Mapper+
USGS	United States Geological Survey
GRanD	Global Reservoir and Dam
NID	National Inventory of Dams
USACE	U.S Army Corps of Engineers
RVA	Range of Variability Approach
IHA	Indicators of Hydrologic Alteration
SD	Standard deviation
HA	Hydrologic Alteration
MLC	Maximum Likelihood Classifier
DOE	Department of Energy
Cms	Cubic meters per second
m^3/s	Cubic meters per second
MW	Mega Watt
V_c	Change of Riparian vegetation
K	Constant governed by local geographical factors
$T_v^{\propto}$	Temporal time stamp

S_c^{β}	Storage capacity of the dam
T_l^{γ}	Long-term average temperature
P_l^{δ}	Long-term average precipitation
$<$	Less than
$>$	Greater than
$=$	Equal to

ACKNOWLEDGMENTS

I wish to express my sincere gratitude to my adviser and mentor, Dr. Sagy Cohen, for his dear advice, guidance, encouragement and provision of a contented atmosphere for me to carry out my research, successfully.

I would also like to extend my appreciation to my committee members Drs. Eben Broadbent and Barabara Rasaiah for providing me advice and guidance to overcome methodological challenges and better argue a scientific premise.

Most of all I would like to thank my wife Nishani for giving me interesting lines of thought which sparked remarkable research solutions in me, and for being the shoulder to fall on during difficult times.

I regret not being able to mention the names of each and every one individually, but your contribution is highly cherished and prized in the successful completion of this research.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

CHAPTER 1

INTRODUCTION

The importance of a river's flow regime for sustaining biodiversity and ecological integrity is well established (Poff *et al*., 1997; Hart and Finelli, 1999; Bunn and Arthington, 2002). Streamflow is viewed as a 'maestro' (Walker *et al.*, 1995) or 'master variable' (Power *et al*., 1995) that shapes many fundamental ecological characteristics of riverine ecosystems (Poff and Zimmerman, 2010). It has been proven throughout scholarly history that the movement of water across the landscape influences the ecology of rivers across a broad range of spatial and temporal scales (Vannote *et al*., 1980; Junk *et al.,* 1989; Poff and Ward, 1990; Poff *et al*., 1997). To be noted, however, is that it is not only the volume of water that is important, but also the timing, duration and frequency of water flows (Richter *et al*., 1997).

Humans have been exploiting riverine environments since pre-historical times. However, growth in human populations, greater urbanization and industrial development in recent centuries has led to dramatic acceleration in alteration of freshwater systems worldwide. An estimated two-thirds of the freshwater flowing to the oceans is obstructed by approximately 40,000 large dams (defined as more than 15 m in height) and more than 800,000 smaller ones (McCully, 1996; see Tharme, 2003). Many additional rivers are constrained by artificial levees or dikes. These hydrological alterations - to ensure water for agricultural, industrial, and domestic purposes; for hydroelectricity; or for flood protection - have changed ecosystem structures and processes in running waters and associated environments the world over (Nilsson and Berggren, 2000). Globally, existing and projected future increases in water demands prompted by the increasing world population has resulted in an intensification of the complex conflict between the development of rivers as water and energy sources, and their conservation as biologically diverse, integrated ecosystems (Dynesius and Nilsson, 1994; McCully, 1996; World Commission on Dams (WCD), 2000; see Tharme, 2003).

Riparian plant communities have a central ecological role in riverine ecosystems. Riparian ecosystems occupy the ecotone between upland and aquatic realms. More precisely, the riparian ecosystem can be defined as the stream channel between the low- and high-water marks plus the terrestrial landscape above the high-water mark (where vegetation may be influenced by elevated water tables or extreme flooding and by the ability of the soils to hold water; Naiman *et al*., 1993). The characteristics of natural riparian zones vary with the size of the river, from narrow and relatively simple strips of land along headwater streams, to heterogeneous floodplains many kilometers wide along lower reaches of major rivers (Nilsson and Svedmark, 2002). Riparian ecosystems offer habitats for many species, function as filters between land and water, serve as pathways for dispersing and migrating organisms, provide food resources, stabilize geomorphic properties along banks and floodplains, provide energy subsidies to aquatic and terrestrial ecosystems, and have many other economic and recreational values (Naiman *et al*., 1993; Naiman and Décamps 1997; Arthington and Pusey, 2003).

It has been demonstrated in many scholarly works that riparian vegetation composition, structure and abundance are governed to a large degree by river flow regime and flow-mediated fluvial processes (Mahoney & Rood, 1998; Karrenberg, Edwards & Kollmann, 2002; Middleton, 2002; see Merritt, *et al*., 2010). For example, when floods inundate floodplain soils, the oxygen available to plant roots is depleted rapidly. The duration of oxygen stress associated with the duration of flooding can thus directly influence the composition and productivity of riparian vegetation species and communities (Richter and Richter, 2000). Floods also indirectly shape riparian ecosystems through their influence on sediment erosion and deposition. Floods build and reshape floodplains by driving the lateral migration of river channels, effecting cutoffs of meander bends, and eroding and depositing sediments on the floodplain surface (Shankman 1993; Scott *et al*., 1996; see Richter and Richter, 2000). These geomorphic changes have significant implications for the successional dynamics of riparian ecosystems (Pautou & Decamps 1985; Malanson 1993; see Richter and Richter, 2000). Today, the majority of the world's large rivers have a regulated water flow (Grill *et al*., 2015), and modification of flow regimes has resulted in extensive alteration of riparian vegetation communities (Jansson *et al*., 2000; see Nilsson and Berggren 2000).

A major modifier of streamflow regimes, dams, has profound effects on the river riparian vegetation communities (Dynesius and Nilsson 1994; Graf 1999). Dams can alter the downstream flow regime by affecting total flow quantity, water quality, and the magnitude, seasonal timing, duration, and rate of change of specific flow events. Dams often result in hydrologic 'fragmentation' or disconnection of the fluvial system, decoupling the affected river reach and its biotic systems from its natural flow regime and causing spatial disconnection, longitudinally of upstream and downstream reaches, and laterally of the river from its floodplain (Hu *et al*., 2008). These effects can be especially pronounced in arid and semiarid settings where natural flow is highly variable (Davies *et al*. 1994; Shafroth *et al*., 2002) and reservoir storage capacity is large (Graf 1999). Altered flow regimes may cause changes in plant species richness (Nilsson *et al*., 1991; Jansson *et al*., 2000, see Nilsson, and Svedmark, M, 2002), plant growth and productivity (Stromberg & Patten, 1990; see Nilsson, and Svedmark, 2002), community composition (Merritt & Cooper, 2000; Merritt & Wohl, 2006; see Nilsson, and Svedmark, 2002) and most importantly, loss of riparian forests (Rood & Mahoney, 1990; Pettit and Froend 2000; Braatne *et al*., 2007; see Nilsson, and Svedmark, 2002). Hence the recognition of riparian areas as good indicators of environmental change caused by flow alterations that are driven by dam operations (Auble *et al*., 1994; Nilsson and Berggren, 2000).

There is a growing need to predict the impacts on the river riparian system to set water management targets that accommodate riverine biota and socially valuable goods and services associated with riparian ecosystems. This necessity has spawned to what amounts to a new scientific discipline of *in-stream flow modeling and design*. The primary application of in-stream flow models has been the design of 'environmentally acceptable' flow regimes to guide river management (e.g. to manage dam operations and water diversions). Such models have been invaluable in developing and implementing management practices aimed at improving effective use of water. Traditionally, the concept of river flows focused on the paradigm of a minimum flow level; this is based on the idea that all river problems are associated with low flows and that, as long as the flow is kept at or above a critical level, the river ecosystem will be conserved. This concept either contained no biological component or considered merely one or few target species, and thus is not considered as comprehensive (Reiser *et al*., 1989).

This has led to an accelerating interest in developing a general, quantitative understanding of riverine ecosystem responses to various types and degrees of flow alteration (Poff and Zimmerman, 2010) and the development of the concept of Environmental Flow (E-flow). A vast body of scientific research has accumulated supporting a natural flow paradigm (a holistic approach mimicking a natural flow regime; Poff *et al*., 1997), where the flow regime of a river, comprising the five key components of variability, magnitude, frequency, duration, timing and rate of change (a holistic approach), is recognized as central to sustaining biodiversity and ecosystem integrity (Poff and Ward, 1989; Karr, 1991; Richter *et al*., 1997; Rapport *et al*., 1998; Rosenberg *et al*., 2000; see Tharme, 2003). Environmental flows provide critical contributions to river health, economic development and poverty alleviation. They ensure the continued availability of the many benefits that healthy river and groundwater systems bring to the environment and society. This requires negotiations between stakeholders to bridge the different interests that compete for the use of water. The reward is an improved management regime that guarantees the longevity of the ecosystem and seeks to find the optimal balance between the various uses. It has been given various names, including the environmental flow regime, instream flow, environmental allocation or ecological flow requirement.

It is interesting to note, however, that although holistic environmental flow methodologies where the natural flow paradigm of rivers is used as a foundation to set river management targets are widely used in Australia and many other countries in the southern hemisphere, they are yet to be explored in depth in the northern hemisphere (Tharme, 2003; Acreman *et al*., 2014; Warner *et al*., 2014). Thus, a research niche is identified for setting river management targets using holistic flow approaches.

It is also of concern that there seem to be only a few examples of water-regulation projects for which the effects on riparian processes have been described in reasonable detail before construction; all developments have been pursued with little understanding or appreciation of the ecological consequences to riparian zones (Nilsson and Berggren, 2000; Alldredge and Moore, 2014). In this context, it is evident that water-resource decisions would benefit if they were informed beforehand by such quantitative predictions of the ecological effects of varying degrees of streamflow alteration.

Biological and physical processes in riparian zones occur at a variety of spatiotemporal scales. To date, free-flowing and regulated rivers have been studied on somewhat different scales. Although developments in the ecology of riparian systems along free-flowing rivers have focused on entire rivers or catchment areas (Ward and Stanford, 1997), knowledge of the effects of hydrological alterations still emphasize local case studies (i.e., individual dams). This difference in scale is due in part to dams being considered controversial and research funding is, therefore, related to the immediate area of individual projects rather than entire river systems with multiple dams (and dam operators). To alleviate this discrepancy, there is a need to increase both the spatial and temporal scales at which regulated riparian systems are studied. In other words, the effects of regulated riparian systems on regional scales, over short and long time periods, should be explored (Nilsson and Berggren, 2000; Shafroth *et al*., 2002; Merritt *et al*., 2010).

In this study, a holistic environmental flow approach for determining stream flow requirements to sustain native riparian vegetation growing along channel margins is explored. The insights drawn from this study may improve restoration of downstream ecosystems of already regulated rivers and set river management targets for unaltered rivers where damming is proposed. Consequently, assessing similarities among flow regimes and characterizing broad categories of hydrologic patterns and responses of riparian vegetation can be useful for developing ecological generalizations among rivers in different regions and transferring information from well-studied rivers to rivers with limited amount of data. The hypotheses tested in this study are (1) there is a reduction in the river flow regime below the dam subsequent to dam construction, (2) the change in riverflow negatively affects riparian vegetation and (3) the regional climates of the dam location affects the recovery of riparian regions in the long run.

Specific aims of the study are to (1) quantify the degree of hydrologic alteration associated with dam operations of sixteen locations across the contiguous United States by comparing the hydrologic regimes from pre- and post-impact time frames using a holistic environmental flow methodology; (2) assess the temporal change in riparian vegetation extent in the downstream region of the dam locations using satellite imagery; (3) relate the change in below-dam riparian vegetation extent to the severity of streamflow alteration at the sites; (4) evaluate the effects of regional climates on long-term recovery of riparian zones; and (5) assess the feasibility of using this approach for river restoration and management and set river management targets for unaltered rivers where damming is proposed.

CHAPTER 2

STUDY AREAS

The domains investigated in this study were sixteen (16) locations in the contiguous United States. The rationale for selecting these sites were twofold: (1) the availability of satellite imagery of Landsat Thematic Mapper (TM) and/or Landsat Enhanced Thematic Mapper (ETM+), and (2) the availability of United States Geological Survey (USGS) gaging stations above and below the dam location with at least 20 years of discharge data. The gage below the dam specifically had to have records for the post-dam time period. Two databases were used to identify potential dams: (1) the Global Reservoir and Dam (GRanD; http://www.gwsp.org/products/grand-database.html) maintained by the Center for Development and Research, University of Bonn, Germany; (2) the National Inventory of Dams (NID; http://nationalmap.gov/small_scale/mld/dams00x.html) managed by the U.S Army Corps of Engineers (USACE). Figure 1 depicts the geographical distribution of the selected sites and Table 1 lists ancillary information of dams that were evaluated.

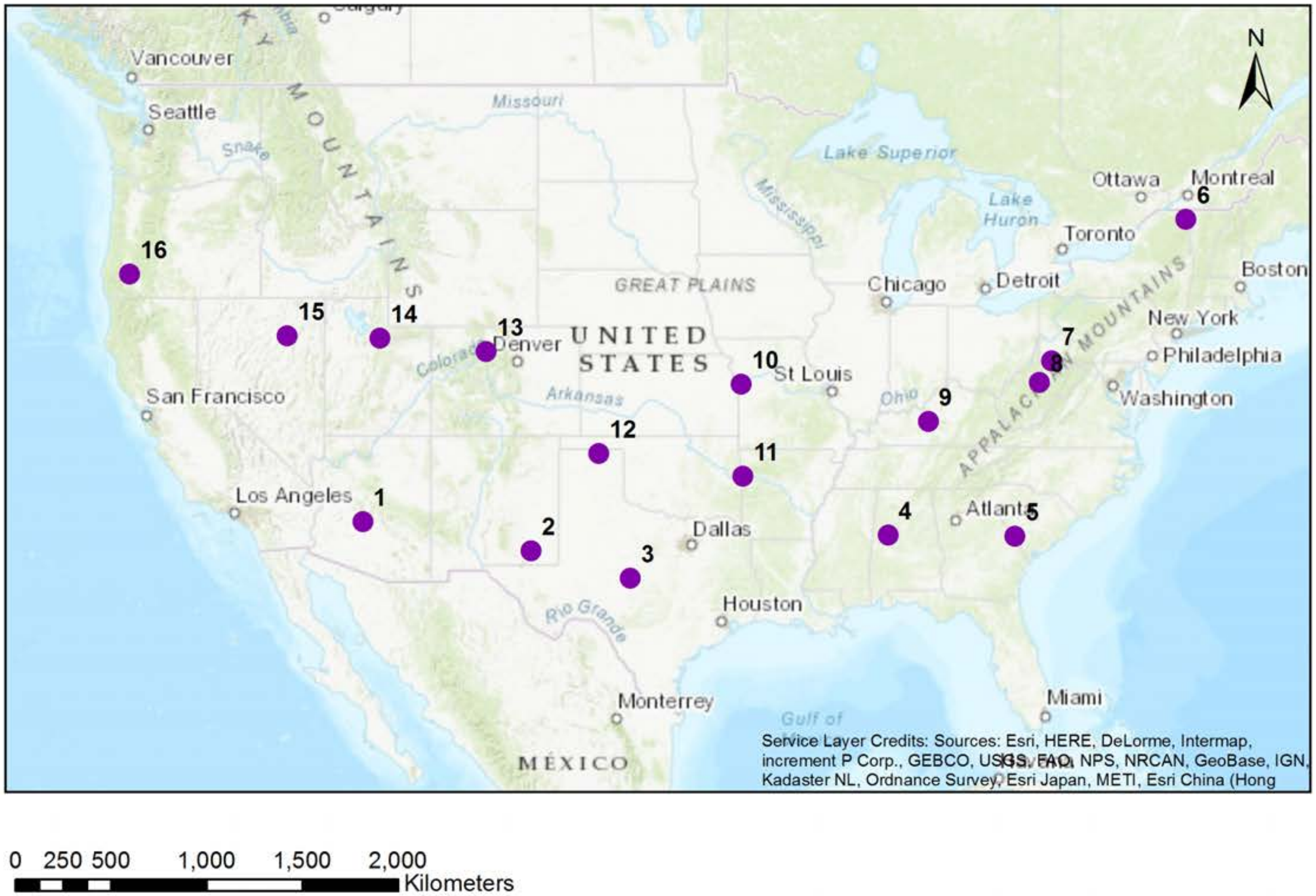


Figure 1. Dam locations with Indices

Table 1. Ancillary information of dams that were used in the study

Dam Index	Dam Name	River	Year of Completion	Normal Storage Capacity (*10^7 m^3)	State
1	New River Dam	New River	1985	5.42	AZ
2	Brantley Dam	Pecos River	1989	42.99	NM
3	Simon Freese Dam	Colorado River	1989	66.65	TX
4	Oliver Lock and Dam	Black Warrior	1992	1.52	AL
5	L Lake Dam	Steel Cr, Savannah River	1986	3.08	SC
6	Kent Falls Dam	Saranac River	1991	0.03	NY
7	Grays Landing Lock and Dam	Monongahela River	1995	1.54	PA
8	Stonewall Jackson Dam	West Fork	1986	5.94	WV
9	Nolin River Fork Dam	North Fork Nolin River	1986	0.05	KY
10	Longview Dam	Little Blue River	1985	2.73	MO
11	Lee Creek Dam	Lee Cr, Arkansas River	1992	0.88	AR
12	Palo Duro Dam	Palo Duro Creek	1991	7.51	TX
13	Ritschard Dam	Muddy Creek	1995	8.14	CO
14	Bor Jordanelle Dam	Provo River	1993	45.89	UT
15	South Fork Dam	South Fork Humboldt River	1988	3.70	NV
16	Galesville Dam	Cow Cr, Umpqua River	1987	5.17	OR

CHAPTER 3

METHODOLOGY

3.1 The Range of Variability Approach

The holistic environmental flow assessment methodology used in this study was based on the Range of Variability Approach (RVA) developed by Richter *et al*. (1997). In order to calculate RVA targets, Richter *et al*. (1997) proposed a method that results in the computation of a representative, multi-parameter suite of hydrologic characteristics or indicators for assessing hydrologic alteration of a river. This is referred to as the Indicators of Hydrologic Alteration (IHA) method (Richter *et al*. 1996; Richter *et al*., 1997; TNC 2009). It encases 33 hydrological parameters (Table 2), which are defined as a series of biologically relevant hydrologic attributes. These attributes are used as the foundation to characterize intra-annual variation in water conditions that are in turn used to determine the range of variability of hydrologic regimes before and after a system has been altered (i.e. RVA targets) by various human activities (i.e. damming).

Table 2. Summary of Indicators of Hydrologic Alteration used in the RVA, and their features

General Group	Regime features	Streamflow parameters used in the RVA
Group 1: Magnitude of monthly water conditions	Magnitude, timing	Magnitude, timing
Group 2: Magnitude and duration of annual extreme conditions	Magnitude, duration	Annual minimum 1-day means
		Annual maximum 1-day means
		Annual minimum 3-day means
		Annual maximum 3-day means
		Annual minimum 7-day means
		Annual maximum 7-day means
		Annual minimum 30-day means
		Annual maximum 30-day means
		Annual minimum 90-day means
		Annual maximum 90-day means
		Number of Zero Days
		Base Flow Index
Group 3: Timing of annual extreme water conditions	Timing	Julian date of each annual 1-day maximum
		Julian date of each annual 1-day minimum
Group 4: Frequency and duration of high and low pulses	Magnitude, frequency duration	Number of high pulses each year
		Number of low pulses each year
		Mean/Median duration of high pulses each year
		Mean/Median duration of low pulses each year
Group 5: Rate and frequency of water condition changes	Frequency, rate of change	Fall Rate
		Rise rate
		Number of Reversals

The hydrologic regime features of the IHA parameter groups (the attributes of river flow that each IHA parameter group takes into consideration) and their ecosystem influences are explained below.

Group 1: 12-monthly mean flows describe the normal flow conditions. The magnitude of monthly water conditions at any given time is a measure of availability or suitability of habitat and defines such habitat attributes as wetted area or habitat volume, or the position of the water table relative to wetland or riparian plant rooting zones.

Group 2: 12 parameters describe the magnitude and duration of annual extreme flows, including 1-, 3-, 7-, 30-, and 90-day annual maxima and minima encompassing the daily, weekly, monthly and seasonal cycles, number of zero flow days and base flow index. The mean magnitudes of high and low water extremes of various durations provide measures of environmental stress and disturbance during the year. Such extremes could regulate soil moisture and anaerobic stresses for riparian vegetation and may be necessary precursors or triggers for the reproduction of certain species and dispersion.

Group 3: Julian dates for 1-day annual maximum and minimum indicate the timing of annual extreme flows. The timing of these occurrences of particular water conditions can determine whether certain life-cycle requirements are met or can influence the degree of stress or mortality associated with extreme water conditions, such as floods or droughts.

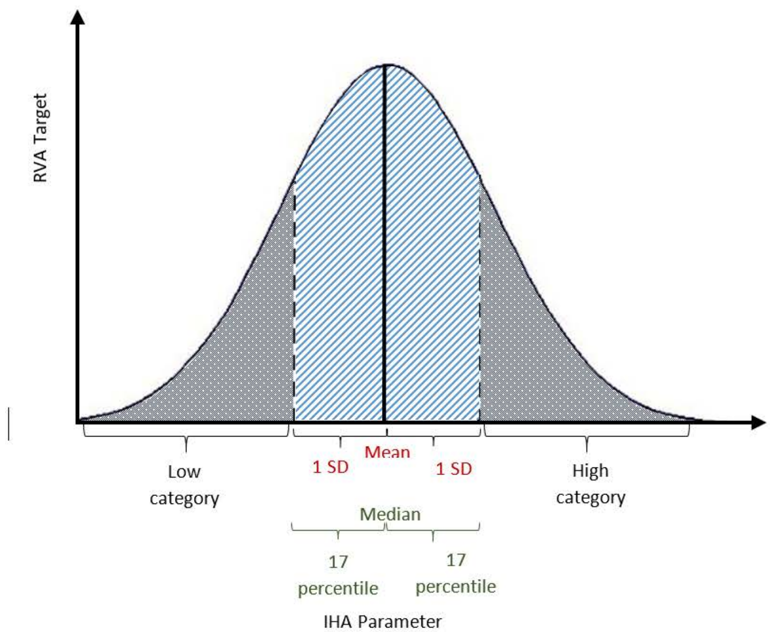
Group 4: Four parameters refer to the frequency and duration of the high and low pulses. The high pulses are periods within a year when the daily flows are above the 75th percentile of the pre-dam period. The low pulses are periods within a year when the daily flows are below the 25th percentile of the pre-dam period. The frequency of specific water conditions, such as droughts or floods, may be tied to reproduction or mortality events for various species, thereby influencing population dynamics. It is also linked to soil mineral availability and nutrient and organic matter exchanges between the river and floodplain. The duration of time over which a specific water condition exists may determine whether a particular life-cycle phase can be completed or the degree to which stressful effects such as inundation or desiccation can accumulate.

Group 5. Fall rate and Rise rate indicate the mean rates of both positive and negative changes of flow on two consecutive days. The number of reversals is the number of times that flow switches from one type of period to another. The rate of change in water condition may be tied to the stranding of certain organisms along the water edge or in pond depressions, or the ability of plant roots to maintain contact with phreatic water supplies.

3.1.1 Range of Variability Approach (RVA) Targets

Thirty-three (33) IHA parameters (Table 2), prior to, and after the alteration for each dam location are calculated separately for every single year of the hydrologic record. One set of the values are for the flow of the river before the construction of the dam and the other set of values after the construction of the dam. Richter *et al*. (1997) stated that river management should be implemented in such a way such that the annual value of each IHA parameter falls within the range of pre-dam natural variation for that parameter. In an RVA analysis, the full range of pre-impact data for each parameter is divided into three different categories (low, middle and high categories) defined by upper and lower RVA targets (Figure 2).

The boundaries between categories are based on either a number of standard deviations away from the mean (for parametric analysis) or percentile values (for non-parametric analysis). If the streamflow record conforms to a Gaussian distribution, parametric statistics are used to calculate central tendency (means) and dispersion [range limits (low and high) and standard deviation]. If the data record was non-normally distributed, non-parametric central tendencies (medians) and dispersions [range limits (low and high) and coefficient of variation] are calculated. Thus, the management targets for any given parameter are expressed as a range of acceptable values. Richter *et al*. (1997) recommended that the ±1 Standard deviation (SD) value (for parametric distribution of flow records) as RVA boundaries (Figure 2). Values at ±1 SD from the mean will be [(mean – SD) < RVA < (mean + SD)] selected as the RVA targets for each of the 33 IHA parameters. In some instances, due to skewness in the distribution of the pre-dam annual values for certain IHA parameters, the mean – 1 SD values fall outside (below) the pre-dam low range limits. For those parameters, the pre-dam minima of their range were selected instead. For non-parametric distribution of flow records a 17-percentile boundary from the median is suggested to be the default for initial RVA targets (Richter *et al*., 1997; Figure 2). This yields an automatic delineation of three categories of equal size: the lowest category contains all values less than or equal to the 33rd percentile; the middle category contains all values falling in the range of the 34th to 67th percentiles; and the highest category contains all values greater than the 67th percentile.



Parametric RVA boundaries

non- parametric RVA boundaries

Figure 2. Comparison between parametric and non-parametric RVA boundaries

The RVA targets suggests that, when considering a modified or altered flow regime, all the calculated IHA parameters (33) should be maintained within this natural variability (e.g. if the pre-dam mean monthly flows of 5 years for the month of January (from a hydrologic record of, for example, 35 years) fell within the ‘low category’, the natural variability suggests that the post-dam mean monthly flows of January should also have 5 values in the low category).

3.1.2 Degree of Hydrologic Alteration

Subsequent to the calculation of the RVA targets for each IHA parameter, the Degree of Hydrologic Alteration, or in other terms the non-attainment of the hydrologic parameter in each of the three categories (low, mid, high) after the construction of the dam, is calculated. First, the expected frequency with which the "post-impact" values of the IHA parameters should fall within each category is calculated. Then the frequency with which the "post-impact" annual values of IHA parameters actually fell within each of the three categories (observed frequency) is computed. The expected frequency is equal to the number of values in the category during the pre-impact period multiplied by the ratio of post-impact years to pre-impact years. The degree to which the RVA target range is not attained is a measure of hydrologic alteration. Finally, a Hydrologic Alteration (*HA*) factor is calculated for each of the three categories as:

$$HA = \frac{(observed\ frequency - expected\ frequency)}{expected\ frequency} \quad \text{...(1)}$$

For example: Dam X has 25 years of pre- and 30 years of post-dam hydrological record. If 16 out of the 30 post-dam average streamflow for the month of January (IHA group 1 parameter) fall in the Middle RVA category, the degree of alteration for this IHA parameter will be:

$$Observed\ Frequency = \frac{16}{25} = 0.64$$

$$Expected\ Frequency = \frac{25}{30} = 0.83$$

$$HA = \frac{0.64 - 0.83}{0.83} = -0.229$$

A positive *HA* value means that the frequency of values in the category has increased from the pre-impact to the post-impact period (with a maximum value of infinity), while a negative value means that the frequency of values has decreased (with a minimum value of -1).

In order to obtain a single 'level of alteration' value for each of the dam locations, explaining the variations in all the 3 categories, the following procedure is followed. First, for each IHA parameter, the values of low, mid and high RVA categories, calculated as stated above, are averaged to get a single degree of hydrologic alteration value.

For Example: If *HA* in the 'low category' = -0.549, 'middle category' = -0.229, and 'high category' = 0.128; average *HA* = (-0.549 + -0.229 + 0.128)/3 = -0.217

Next, the 'absolute values' of these 33 parameters are rescaled between 0% and 100% based on their minima and maxima in order to be comparable across dam sites. According to Richter *et al*., (1997) (1) 0-33% represents low level of hydrological alteration at the dam site (2) 34-67% represents moderate level of alteration, and (3) 68-100% represents a high degree of alteration. Subsequently, the mean of the 33 'absolute' values are calculated and used to determine the overall level of alteration of the river. It is important to understand that the overall level of alteration always reflects the degree of non-attainment of the natural flow regime after the construction of the dam. It does not provide the causation for it (i.e. non–attainment due to a lowered flow regime from the pre-dam era or an increased flow regime). Long-term average pre- and post-dam streamflow was also calculated for all dam locations. If the post-dam mean was higher than the pre-dam mean, the post-dam flow regime (the entire flow paradigm encompassing magnitude, timing of flow and other attributes) was considered to have increased.

3.1.3 Calculation of IHA parameters, RVA targets and Degrees of Alterations

Daily streamflow data for the dam sites was downloaded from USGS gaging stations (U.S. Geological Survey, National Water Information System. Accessed January, 2016 - February, 2017, http://waterdata.usgs.gov/nwis; unless otherwise noted, all streamflow data in this document are from this source). The streamflow record before and after the construction of the dam in each site was at least 20 years in length. The length of the daily mean streamflow record of the pre- and post-dam period varied among gaging stations. For consistency, most series were processed with data lengths of 20-23 years. Missing data values on the long term hydrologic records were estimated based on regression analysis using procedures described in Beale and Little (1975). The Anderson-darling Normality tests (Anderson and Darling, 1954) were conducted on each individual streamflow record to assess the parametric/non-parametric nature of the data using Minitab (version 16.0) statistical software. The Indicators of Hydrologic Alteration (IHA) software (version 7.0) developed by The Nature Conservancy were used to calculate the IHA parameters, the RVA targets and the level of alteration of rivers.

3.2 Remote Sensing of Riparian Vegetation change

Rapidly growing technologies in image analysis and remote sensing provide a powerful tool and are becoming increasingly useful in historical analysis of riparian vegetation mapping and management (Narumalani *et al*., 1997, Congalton *et al*., 2002; Klemas, 2011). The Landsat suite of satellites has been widely used for riparian vegetation change detection since its inception (e.g. Hewitt, 1990; Jensen *et al*., 1995; Congalton *et al*., 2002; Yang, 2007). The reasons for using Landsat images are that they are free, they provide extensive spatial coverage for repeatable observations temporally and spatially, and are low cost in comparison to ground surveying. In this study, Landsat 5-Thematic Mapper (TM) and Landsat Enhanced Thematic Mapper (ETM+) satellite imagery were used. For riparian vegetation change mapping using remotely sensed imagery, two sets of data are required. One set consisting of data acquired before the construction of the dam to make informed decisions about general conditions of the pre-dam environment, and the other acquired after the construction of the dam. In an effort to understand the pre-dam environmental conditions, three images obtained almost on anniversary dates of 3 consecutive years going back from the year that dam construction started were used for each individual dam. The rationale behind selecting 3 images was the availability of imagery for 3 consecutive years from the same time period of the year for dams built during the early 1980s. Although utilization of additional imagery would have given more precise pre-dam base line conditions, the compromise of losing dam locations due to non-availability of more than 3 years of pre-dam data was evaluated, and decided upon, in accordance. In a possible circumstance that the 3 pre-dam images did not capture extreme conditions in the study site (e.g. droughts), hydrographs of pre-dam flows were studied to understand unusual peaks/valleys of flow changes which acts as a proxy of climatic properties of the region. Upon analysis, since there did not exist drastic drops/increments in flows (<10^{th} Percentile or >90^{th} Percentile; Gregor, 2012) in the flow time series, 3 years of pre-dam imagery was decided as adequate to obtain the average pre-dam riparian vegetation extents. The analysis of post-dam riparian vegetation extent was performed to identify the temporal changes in riparian vegetation extent. The selected temporal time frames were: immediately after the completion of the dam, 1 year post-completion, 3 years post-completion and 5 years post-completion.

Landsat 5- TM and Landsat 7 ETM+ satellite imagery with <20% cloud cover were downloaded from USGS Earth Explorer (United States Geological Survey Earth Explorer. Accessed January, 2016 - February, 2017, http://earthexplorer.usgs.gov). Although these images are georeferenced and corrected for basic atmospheric perturbations (radiometric corrections) beforehand by the EROS Data Center, further radiometric corrections were carried out in order to eliminate haze and ancillary noise (e.g. imagery acquired through faulty channels) for image enhancement. Care was also taken to acquire all imagery of one particular location during a certain month(s) in order to minimize atmospheric effects that would later affect vegetation analysis. Erdas Imagine®- 2015 Image processing software (Hexagon Geospatial, Norcross, GA, USA) was used for image pre-processing and subsequent data manipulation of this study.

Since this study only looked at changes in riparian vegetation below the dam, for each individual dam location, a riparian vegetation buffer was created below the dam. Because there are no agreed buffer distances for riparian vegetation, the length and the width of the buffer depended upon the stream order of the river that the analysis was performed on (e.g. Correli, 2005; Delong and Brusven, 19; see Klemas 2014; Yang, 2007). However, the actual riparian zones are never uniform, even within the same stream order (Yang, 2007). Therefore, user knowledge and expertise of the region and topography, and web and scholarly articles (e.g. Castelle *et al*., 1994; Klemas 2014) were used to delineate the riparian buffers. Buffer widths ranging from 3 to 200 m and lengths ranging from 300 – 1000m were used in this study. As a result, widths and lengths of no two stream segments were similar to each other. The same buffer was used to analyze riparian zones from the three pre-dam and four post-dam images of each individual dam location.

3.2.1 Supervised Classification vs. Spectral Indexing

Satellite image analysis of riparian vegetation presents two options: 1) a user-directed mechanism (i.e. Supervised Classification) or 2) different band combinations of the satellite sensor in vegetation indices, to extract vegetation features on the imagery. Supervised classification of remotely sensed imagery has been demonstrated to be a robust method to classify riparian vegetation (Congalton *et al*., 2002; Johansen *et al*., 2007; Makkeasorn *et al*., 2009). The Supervised Classification technique is based on the idea that a user can select sample pixels in an image as representatives of a specific spectral signature class (endmembers; e.g. vegetation). Subsequently, all the image pixels are classified based on the maximum likelihood that they are similar to one of the user-defined classes. Supervised classification based on the Maximum Likelihood Classifier (MLC) was performed to identify the following information classes in the buffer zone: water, vegetation, barren land and urban. Vegetation pixels were extracted for the three pre-dam scenarios and four post-dam scenarios subsequently and the corresponding areas of these pixels were calculated. The pre-dam vegetation areas were averaged out to obtain baseline pre-dam environmental conditions.

Supervised classification was used in this study since it has been proven far superior to spectral indexing methods with regards to classification accuracies. Narumalani *et al*. (1997), Johansen *et al*. (2007) and Bagan *et al.* (2005); see Xie *et al*., 2008 all reported higher classification accuracies under supervised classification with a maximum likelihood classifier as opposed to the use of spectral indexing. Also, the differences in capabilities of vegetation indices on different topographies and climates makes supervised classification a more suitable tool for studies conducted on larger geographical scales (Jackson, 1983; Kerr *et al*., 1989; Nicholson *et al*., 1990; see Makkeasorn *et al*., 2009).

3.2.2 Accuracy assessments and riparian vegetation change calculation.

The accuracy of the supervised classification algorithm was assessed via an accuracy assessment. A false color composite (for improved visualization of feature classes of interest) of the same satellite imagery was used for the process. Known pixels of vegetation on the classified imagery, independent of those used to train the MLC were randomly selected, and accuracy assessments were carried out for the already classified three pre-dam scenarios and the four post-dam time steps separately, for each individual dam location. User's accuracy, producer's accuracy, overall accuracy and the kappa statistic were calculated for each scenario. User's accuracy in this instance is the fraction of correctly classified pixels with regard to all pixels classified as a specific class (e.g. vegetation) in the classified image, or in other words, the possibility that a given pixel on the classified image belongs to a certain land class type. The producer's accuracy is defined as the ratio between the numbers of pixels classified on an image to the number of pixels of that feature class in the area of interest in reality. The overall accuracy is calculated as the total number of correctly classified pixels of each class divided by the total number of test pixels in the riparian buffer. The kappa statistic is a reflection of pixels that were correctly classified into a feature class by chance. Based on the accuracies a 'mean overall accuracy' was calculated for the three pre-dam images to appropriately reflect pre-dam environmental conditions.

Post-classification change detection of below-dam riparian zones were carried out subsequently. The pre-dam vegetation was compared to post-dam time steps. The 'mean overall accuracy' for a given pre-dam scenario was multiplied by the average pre-dam vegetated area within the buffer. This results in the actual average pre-dam vegetated area for a given dam location. Subsequently, the same operation (i.e. overall accuracy multiplied by the vegetated area within buffer) is performed on all four post-dam scenarios. The actual post-dam vegetation values are subtracted from the pre-dam values to get the actual change in riparian vegetation within the buffered region, for a given location.

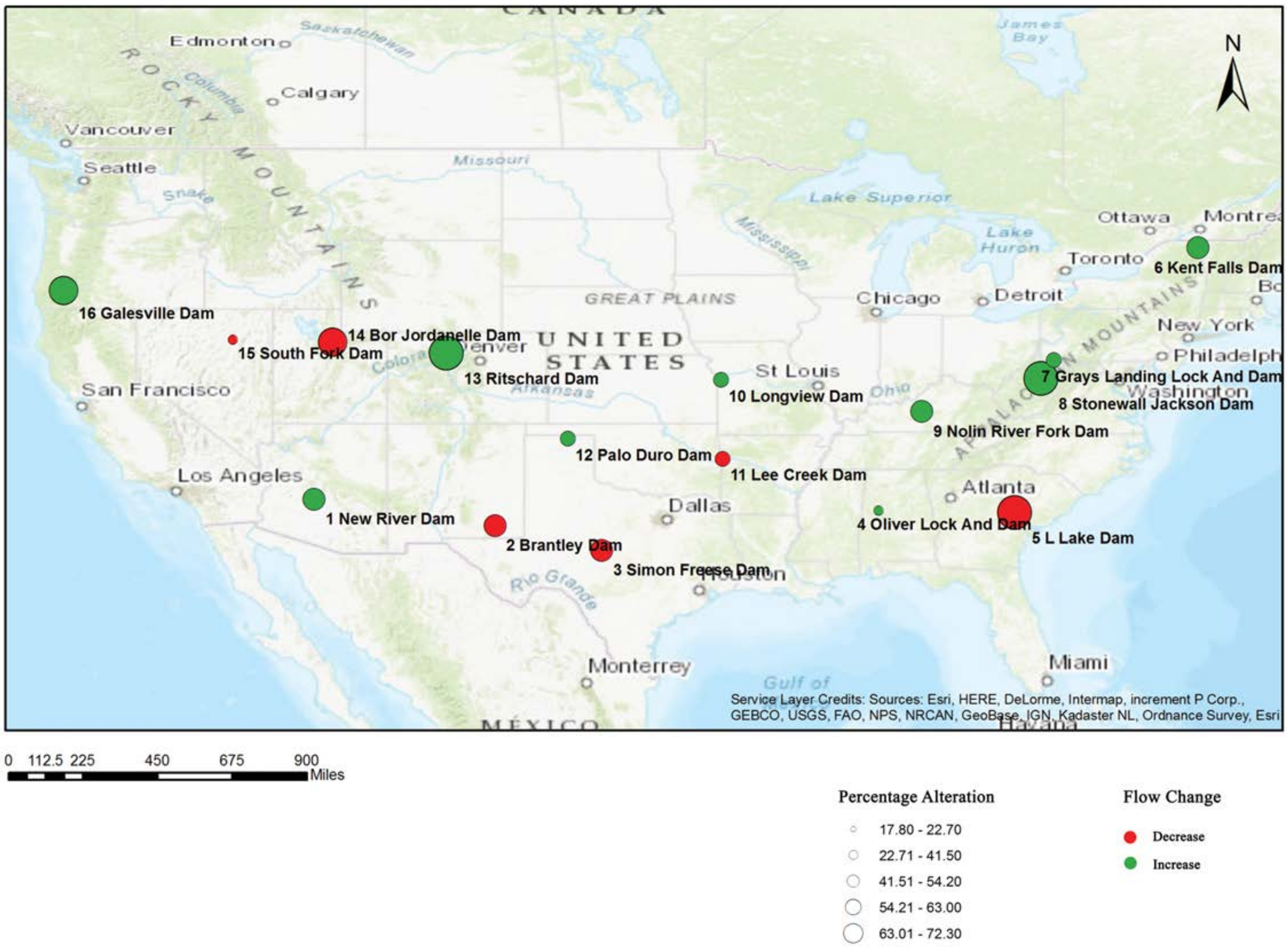
CHAPTER 4

RESULTS AND DISCUSSION

4.1 Test for normality of hydrologic records

The Anderson Darling tests conducted for each individual hydrological record yielded non-parametric distributions for all the hydrologic records. At all instances, the two tailed tests for daily discharge (cms) at a 95% confidence level the test yielded significances (P) of less than 0.05. Therefore, the null hypothesis was rejected and the alternative hypothesis, (i.e. the dataset is not normally distributed) was accepted. Thus, all RVA calculations were performed based on a “median” and “percentile distributions” (see non-parametric RVA boundaries, Figure 2).

4.2 Assessment of hydrologic alteration caused by dam construction using the RVA approach



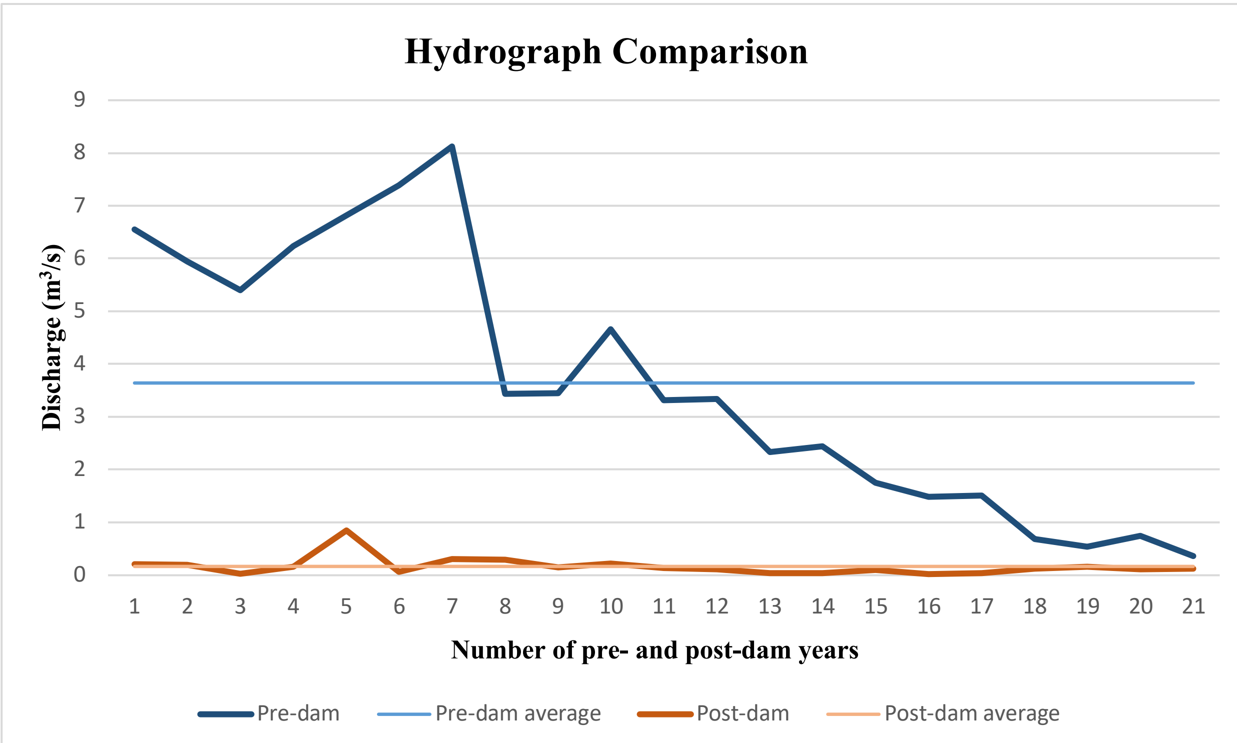
Note: The dam index is followed by the name of the dam at the bottom right of the location.

Figure 3. The levels of alterations and flow regime changes at dam locations

The general levels of alterations of the natural flow regime after the construction of the dams varied between ~17% and ~72% among all study sites (Figure 3; see appendix 1 for Summary of mean absolute values of the 33 indicators of hydrologic alteration at the sixteen study sites). Of the 16 study locations, the level of alteration was 'low' (0-33%) at 2 locations, 'moderate' (34-66%) at 11 locations and 'high' (67-100%) at 3 locations. High levels of alterations, which are of most environmental concern was observed at the L-Lake Dam on Steel Creek, Savannah River (Dam Index: 5; Figure 1), Stonewall Jackson Dam on the Westfork River (Dam Index: 8) and Ritshard Dam on Muddy Creek, Colorado River (Dam Index: 13). Of the two low level alterations one was due to an increase in the magnitude of flow in the post-dam flow regime, and the other was due to a decrease. The 11 moderate alterations consisted of 7 flow regimes increases and 4 decreases. Of the three high level alterations, two were due to increase of the flow magnitude compared to the pre-dam, natural range. The flow regime characterization and of the pre-dam and post-dam scenarios of the three most highly-altered dams, L-Lake, Stonewall Jackson, and Ritshard, are discussed below.

L-Lake dam

The L-Lake dam was built by the U.S Atomic Energy Commission (predecessor of Department of Energy – DOE) to dissipate the thermal effluent of the L-nuclear reactor at the Savannah River Site (U.S. DOE, 1996). In an effort to reduce annual pumping costs from the river to the reactors by $930,000, the DOE decided to discharge a minimum flow of only 0.283 m^3/s to the downstream of L-Lake dam in order to hold the lake at normal operating levels at all times (U.S. DOE, 1996). This concept of 'minimum flow' which leads to drastic levels of natural flow regime alterations has been refuted by many scholars (Richter *et al.*, 1997; Poff and Zimmerman, 2010). Appendix 2 shows the differences in pre-dam and post-dam flow changes of the 33 parameters while Figure 4 shows the pre- and post- construction changes in the magnitude of flow.



Note: 'Pre-dam' represents the annual average discharge time series while 'Pre-dam average' denotes the average discharge for the selected time period. 'Post-dam' and 'Post-dam average' represent post-dam annual average discharge time series and post-dam average discharge, respectively. The running numbers from 1 to 21 represent the length of the pre- and post- dam time period that was considered.

Figure 4. Hydrograph comparisons of pre- and post-dam flow magnitudes of L-Lake Dam

1) In the monthly mean flow data, in all months, the degree of alterations were high. The alterations varied between 75% and 84%. The decrease in the monthly mean flows suggests a drastic drawdown in the water table in downstream areas which consequently affect the riparian plant rooting zones.

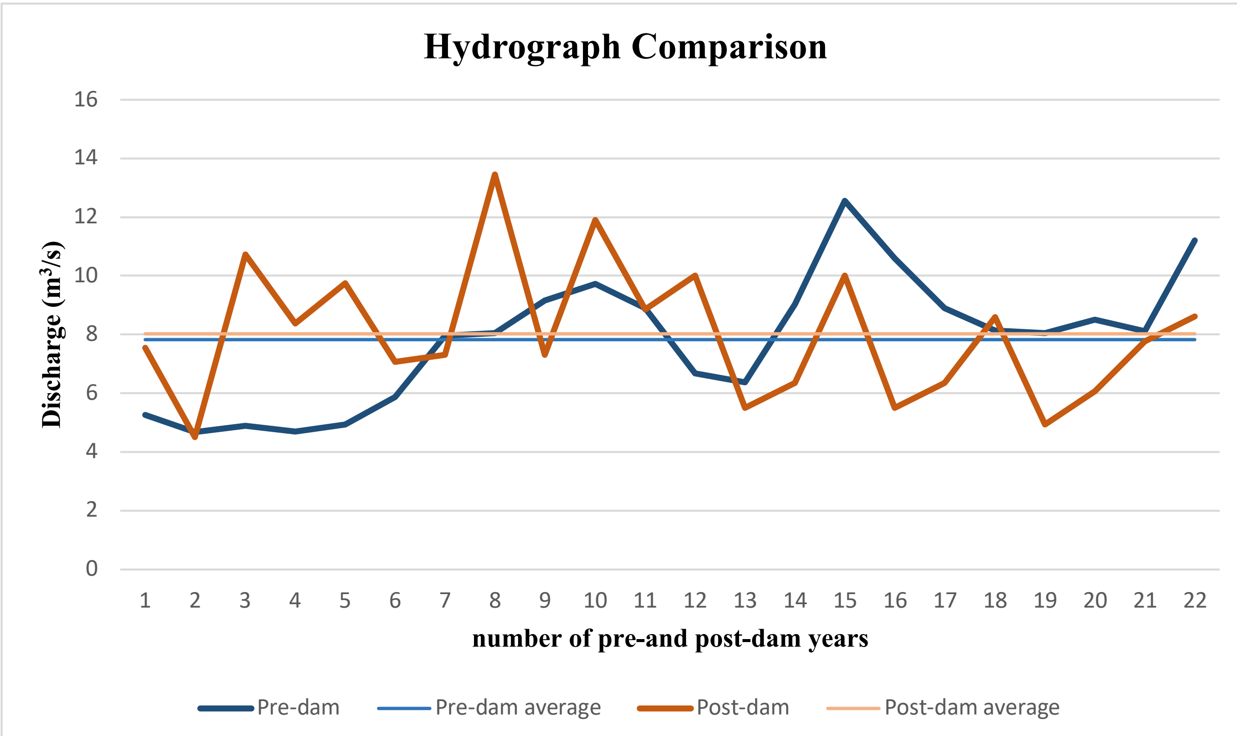
2) The medians of annual 1-, 3-, 7-, 30-, 90-day minimum and 1-, 3-, 7-, 30- and 90-day maximum for the post-impact period decrease significantly. Results indicate that the daily, weekly, monthly and quarterly maximum/minimum flow cycles are negatively influenced by reservoir regulation. With the exception of the base flow index and the number of zero discharge days, all parameters fluctuate between 79-84%.

3) Pulsing frequencies of the flow (Group 4): The number of high and low pulses has dropped. This is a byproduct of extended periods of storage within the reservoir by the DOE for hydro power generation, in order to reduce pumping costs from the Savannah River. Even when the water is released it doesn't mimic the pre-dam high pulsing behavior. The fall rate (the difference in discharge between two consecutive days) has doubled (i.e. level of alteration is a 100%) which means that the plant-available water downstream of the dam during low water conditions has reduced by a factor of two.

Stonewall Jackson dam

The Stonewall Jackson Dam that creates the Stonewall Jackson Lake was authorized and approved by the Flood Control Act of 1966. The purposes of the project, as stated in the authorizing legislation, are flood protection, low flow augmentation for water quality, water supply, fish and wildlife enhancement, hydropower and recreation (http://www.lrp.usace.army.mil/Missions/Recreation/Lakes/Stonewall-Jackson-Lake/). The project, completed in 1990, is the most recent addition to Pittsburgh District's 16 flood control projects. Unlike the L-Lake dam, the hydrological alteration in this dam was due to an increase in the flow paradigm.

The alterations of the 33 IHA parameters of the Stonewall Jackson Dam are given in Appendix 3. The comparable hydrograph of flow magnitudes is depicted in figure 5.



Note: 'Pre-dam' represents the annual average discharge time series while 'Pre-dam average' denotes the average discharge for the selected time period. 'Post-dam' and 'Post-dam average' represent post-dam annual average discharge time series and post-dam average discharge, respectively. The running numbers from 1 to 22 represent the length of the pre- and post- dam time period that was considered.

Figure 5. Hydrograph comparisons of pre-and post-dam flow magnitudes of Stonewall Jackson Dam

1) Medians of monthly flow throughout the post-impact period indicate an increase compared with that in the pre-impact period. The deviations of all months were above 68% and reached a maximum of 80%. The increase in flow suggests additional water availability for downstream riparian vegetation and terrestrial animals. Although increased water downstream post-dam

construction is counter intuitive, literature suggests reasoning for such instances. The major cause for increased flow is the additional release of water from upstream reservoirs when the volume of water flowing into a reservoir is less than needed to meet systemwide flow requirements. This happens especially during the summer months and results in increased post-turbine-use flow downstream. During certain other years water may also be released from reservoirs after significant storm events to ensure adequate flood storage capacity thus increasing downstream flow.

2) Hydrologic alteration of extreme values: High hydrologic alterations of 7-, 30-, 90-day minimum, 1-, 3-, 7-day maximum (Appendix 3) suggest reduction of anaerobic and soil moisture stresses in plants, and providing more opportunity for plant colonization and distribution of plant communities in the floodplains.

3) The Julian dates of each annual 1-day minimum values move backward from the 240th day in the pre-impact period to the 179th day in the post-impact period; the Julian dates of each annual 1-day maximum values move backward from the 337th day in the pre-impact period to the 65th day in the post-impact period.

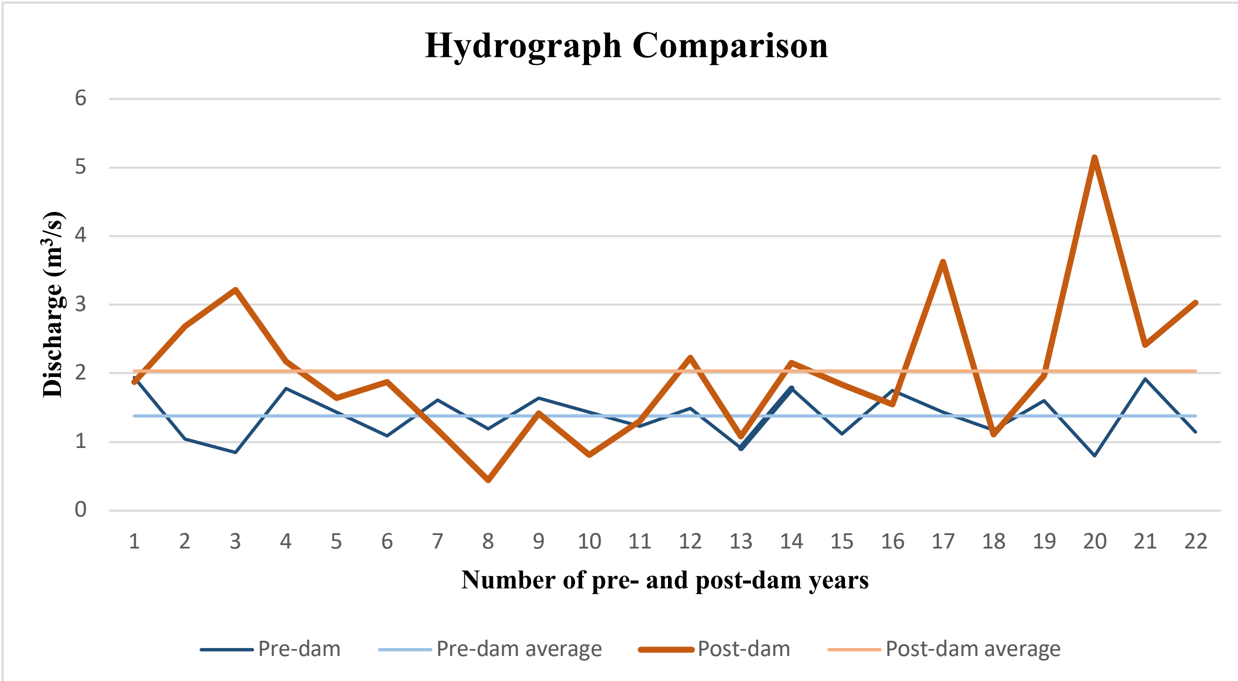
(4) Hydrologic alteration of frequency and duration of high and low pulses: the pulsing behavior below the dam has been severely affected. The number of low pulses post-dam has dropped to zero. The number of high pulses has decreased, but the duration of the high pulses have drastically increased. This is also evident by the ~71% alteration of the rise rate.

The reasons for an increase in streamflow observed downstream, post-dam construction, is believed to be due to the use of water storage for irrigation and hydro-power in non-flood seasons which had a direct impact on the mean monthly flows of the river. It could also be a result of the fact that the gaging station that was used to record below dam flows was situated beyond the point where the tailwater (water that is used to spin the turbine) enters the river. Since the tailwater is a massive force of concentrated water, it could also result in increased flow regime. It could also be a result of changes in precipitation patterns in the region, which lead to an increase in post-dam average flow. This is evident by the increasing trend in the pre-dam hydrograph.

Ritshard Dam

Wolford Mountain Reservoir created by the Ritschard dam is a reservoir managed by the Colorado River District, headquartered in Glenwood Springs, CO. The reservoir dams Muddy Creek and is part of the Colorado River watershed. Construction of the reservoir was completed in 1996. Its main uses are municipal water supply and recreational fishing. Of the 3 highly altered dams, Ritshcard had the least alteration with a mean value of 68%. The alteration was also due to increase of post-dam flows.

The alterations of the 33 IHA parameters of the Ritschard dam are given Appendix 4. Figure 6 shows the pre- and post- construction changes in the magnitude of flow.



Note: 'Pre-dam' represents the annual average discharge time series while 'Pre-dam average' denotes the average discharge for the selected time period. 'Post-dam' and 'Post-dam average' represent post-dam annual average discharge time series and post-dam average discharge, respectively. The running numbers from 1 to 22 represent the length of the pre- and post- dam time period that was considered.

Figure 6. Hydrograph comparisons of pre-and post-dam flow magnitudes of Ritschard dam

1) With the exception of the months of April and May, the median flows increased post-dam-construction. This could be due to the fact of holding water within the reservoir for municipal water purposes before the onset of the rainy season in late May. In all other months the deviations (positive) ranged from 67 – 100%.

2) It was interesting to note the high positive deviation (<90%) of the minima values further suggesting increased flow regimes. However, the decrease in medians of the monthly (30 day)

and quarterly (90 day maxima) suggests that although the flows increased as a whole frequency of flow peaks diminished.

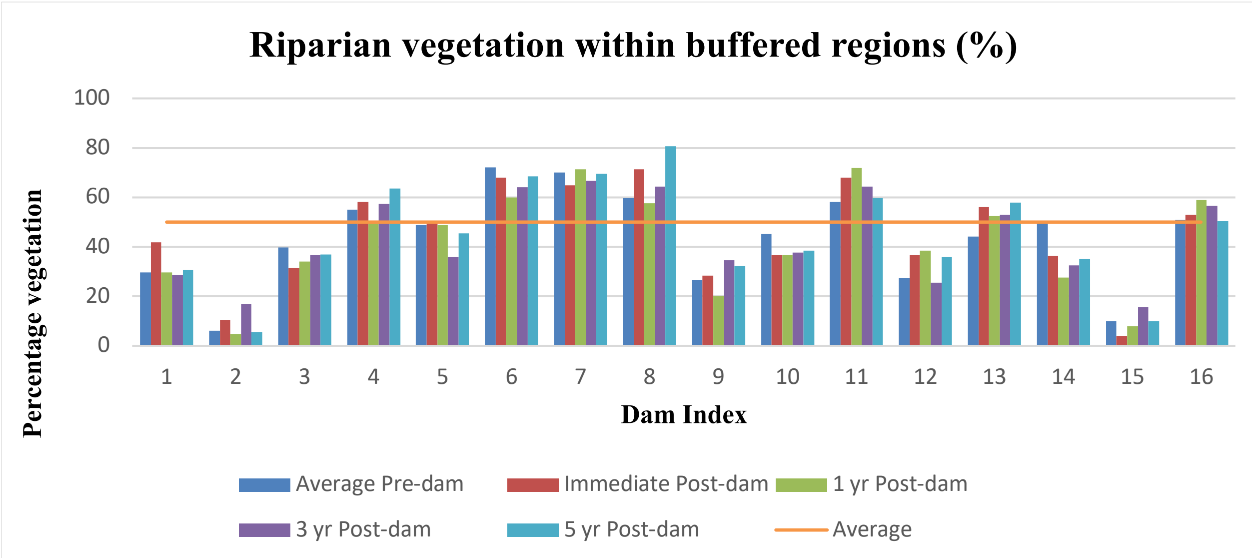
3) In the pulses and pulsing frequencies category (group 4), the number of high and low pulses and their durations both decreased. This could be reflective of the dam operation regulations for water supply.

4.3 Riparian Vegetation Dynamics

Analysis of satellite imagery showed the percentage differences of riparian vegetation within the buffers created at each dam location (Table 3 and Figure 7). The overall accuracy of vegetation classification is given within brackets.

Table 3. Percentage riparian vegetation at each dam location and overall classification accuracy of vegetation (within brackets)

Dam Index	Average Pre-dam (%)	Immediate post-dam (%)	1 yr post-dam (%)	3 yr post-dam (%)	5 yr post-dam (%)
1	30.86 (96.2)	43.34 (96.7)	30.30 (97.9)	29.13 (97.9)	32.55 (94.6)
2	6.31 (95.1)	10.86 (97.8)	5.20 (94.4)	17.47 (96.7)	5.76 (96.6)
3	40.56 (97.7)	32.43 (96.9)	34.56 (98.8)	38.10 (96.2)	37.44 (98.8)
4	57.68 (95.6)	60.69 (95.7)	51.32 (97.8)	58.54 (97.8)	67.89 (93.5)
5	51.81 (94.2)	49.85 (98.8)	50.46 (96.8)	36.02 (99.9)	48.52 (93.6)
6	73.17 (98.4)	69.51 (97.9)	60.80 (98.7)	67.74 (94.6)	70.02 (97.9)
7	72.54 (96.4)	66.42 (97.6)	73.73 (96.7)	69.80 (95.6)	70.29 (98.8)
8	61.17 (97.6)	72.28 (98.8)	59.45 (96.9)	65.15 (98.8)	84.19 (95.7)
9	27.10 (98.4)	29.03 (97.8)	21.13 (95.1)	37.10 (93.5)	32.62 (98.8)
10	46.15 (98.2)	37.26 (98.7)	37.65 (97.6)	40.16 (93.6)	40.22 (95.6)
11	60.02 (96.8)	71.74 (94.6)	74.29 (96.7)	65.17 (98.8)	60.54 (98.8)
12	27.91 (97.6)	37.84 (96.7)	40.26 (95.8)	25.99 (97.8)	37.96 (94.5)
13	45.60 (96.9)	57.52 (97.4)	55.15 (95.2)	57.58 (92.1)	59.13 (97.9)
14	51.25 (97.5)	37.55 (96.7)	28.29 (97.8)	34.79 (93.2)	38.06 (92.1)
15	10.33 (97.3)	4.15 (98.8)	8.06 (96.6)	15.76 (98.8)	10.58 (93.2)
16	54.68 (93.2)	54.04 (98.1)	60.16 (97.8)	61.34 (92.2)	53.44 (94.2)



Note: The kappa statistic ranged between 0.89 and 0.94 for the scenarios.

Figure 7. Comparison between percentage riparian vegetation within buffered regions

An assessment of the buffer zones revealed the extent of land cover adjacent to the streamflow alterations. At 8 of the 16 locations, more than 50% of the pre-dam land cover within the buffer was vegetation. The forested watersheds that the dams are located within explain this. The highest percentage of pre-dam vegetation (72%) was recorded at Kent Falls Dam located within the Kent Falls State Park in New York (Dam index 6). Other areas that have relatively less riparian areas are dominated by agricultural and barren land.

The analysis of riparian vegetation over time, subsequent to dam constructions, brought forth interesting observations. There is a general consensus that eliminating or reducing the effects of floods and lowered groundwater levels that follow river regulation changes the species composition of riparian forests (Naiman and Decamps, 1997; Nilson and Berggren, 2000). These changes start a new succession of riparian communities that result in growth of forest types more characteristic of unflooded upland areas (Décamps *et al*. 1988; see Nilson and Berggren, 2000). For example, lowered groundwater levels resulting from river regulation can cause a decline in the reproduction of pioneer species (species with easily dispersed seeds, rapid germination, and rapid root and height growth) followed by a successive dieback of mature individuals (Stromberg *et al*. 1996; see Nilson and Berggren, 2000). With time, invasive plant communities capable of tolerating low water and nutrient levels colonize the riparian environment (Richardson *et al*., 2007). Hence a reduction of riparian vegetation immediately after the construction of the dam, and a subsequent increment over time, is expected. However, this study revealed mixed results; agreements as well as deviations to this general notion. The temporal changes in riparian vegetation extent subsequent to dam construction are shown in Figure 8.

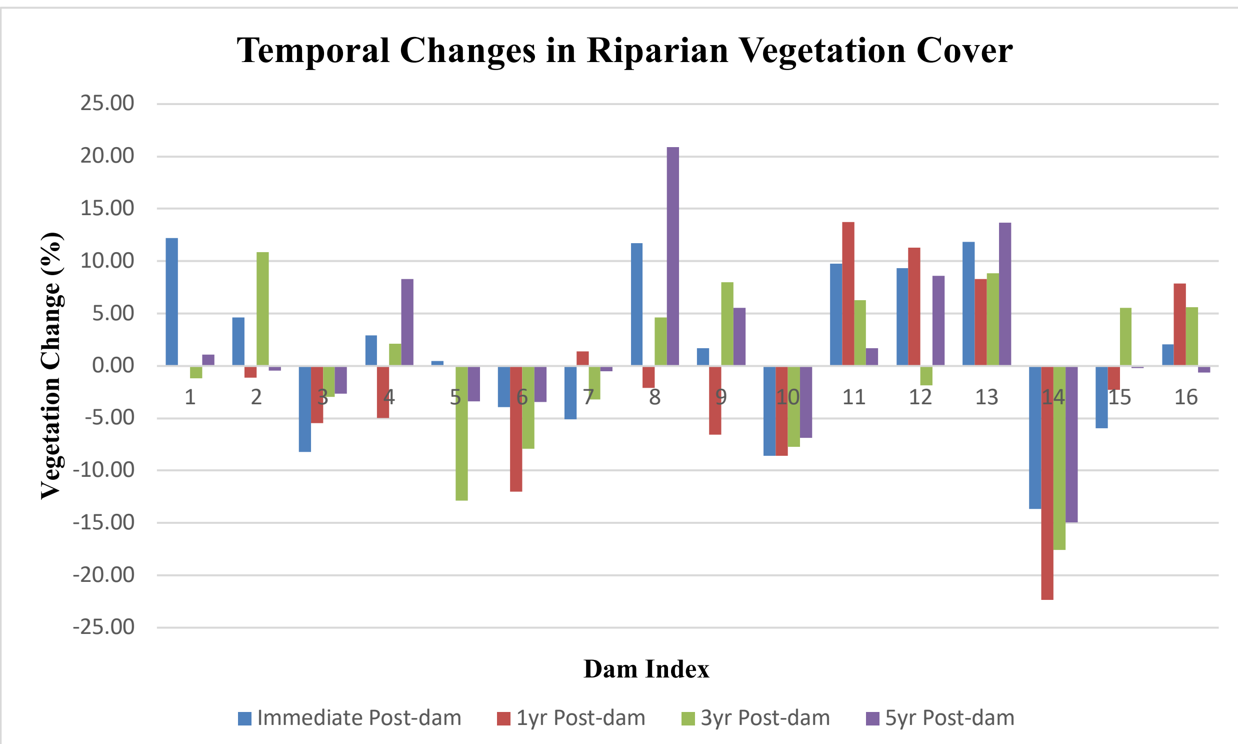


Figure 8. Percentage changes in riparian vegetation cover over time

Ten of the 16 locations studied revealed an increase in riparian vegetation immediately after the construction of the dam. This could be explained by the activities of the construction of the dam itself. Streams and rivers must be diverted to create a dry area to construct the dam. Small rivers and streams are usually diverted through a tunnel, or a channel that is constructed around the side of the dam. However, in the case of larger rivers, it would be impractical and expensive to construct a separate channel to divert the water. Instead, a dry construction pit is formed on one side of the river, leaving the other side open for the water to flow through. The first portion of the dam is constructed in the dry pit. When it is completed, another dry area is formed on the other side of the river, and the remaining part of the dam is built. Meanwhile, the river flows through openings in the completed portion of the dam, and the reservoir starts to fill behind it. The continuous flow of water would let the pioneer species survive while enhancing invasive species growth (tolerant of lower water levels in the dry area) resulting in an increment of vegetation in the entire riparian buffer.

It was also interesting to note that 10 of the 16 study sites recorded a decrease in vegetation 1 year post-completion of the dam, lower than their 'immediate post-dam completion' extents. This phenomenon could be explained by the dynamics between plant dieback and recovery. At the end of the construction of the dam the entire flow of the river is regulated resulting in the start of the dieback of pioneer species and matured trees. This opens up resources for invasive species to settle in over the successive years. The time between this dieback and the recovery is evidenced by the 1 year post-completion vegetation extents. After the 1st year, a trend in increases in vegetation could be observed over time. The gradual recovery of the riparian zone is being demonstrated at the 1 year post-completion mark by dam indices 3, 4, 6, 8, 10, 13, and 14. Although the other study sites did not show a similar pattern at the 1 year post-completion mark, the trend was visible with a timeline shift, either towards the immediate post-dam completion stage or to a later stage (i.e. 3 year/5 year post-completion stages).

4.4 The Relationship between river flow regime alteration and downstream riparian vegetation growth.

In an effort to understand the relationships of the severity of post-dam alteration of the flow regime to the different stages of vegetation cover change, the levels of alteration were correlated against temporal changes in riparian vegetation at each dam location (Figure 9). The level of alteration was considered positive, if the flows increased following dam constructions (as per ‘flow regime change’ in Figure 3) and vice versa. The ‘positive’ and ‘negative’ alteration was warranted for this analysis in order better understand how post-dam flow regime changes (positive/negative) influenced changes (increase/decrease) in below dam vegetation.

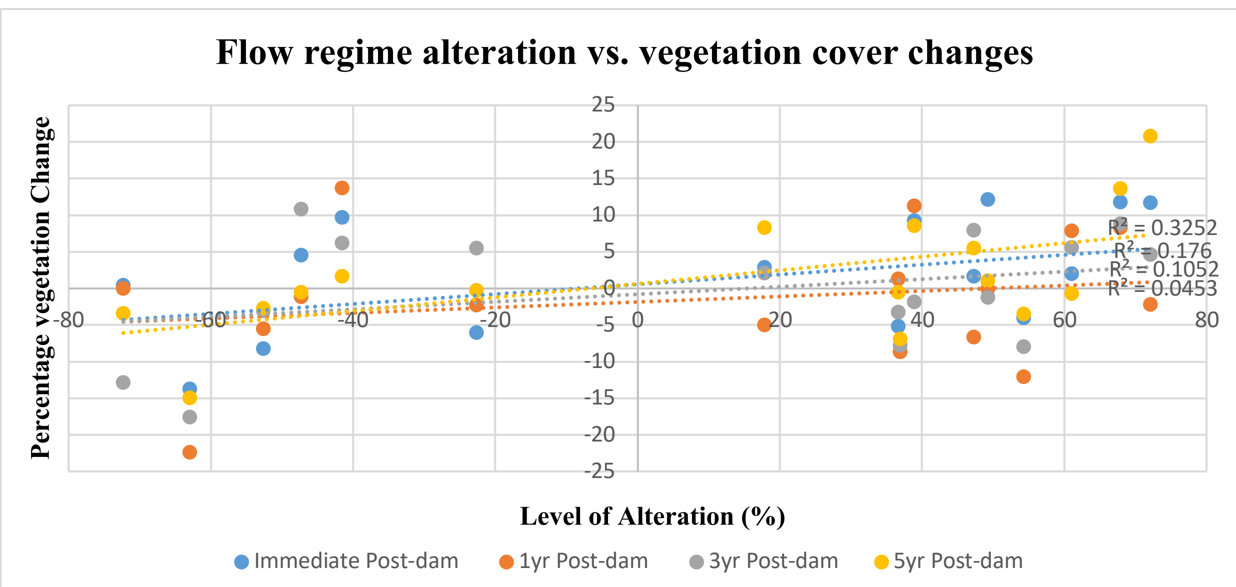
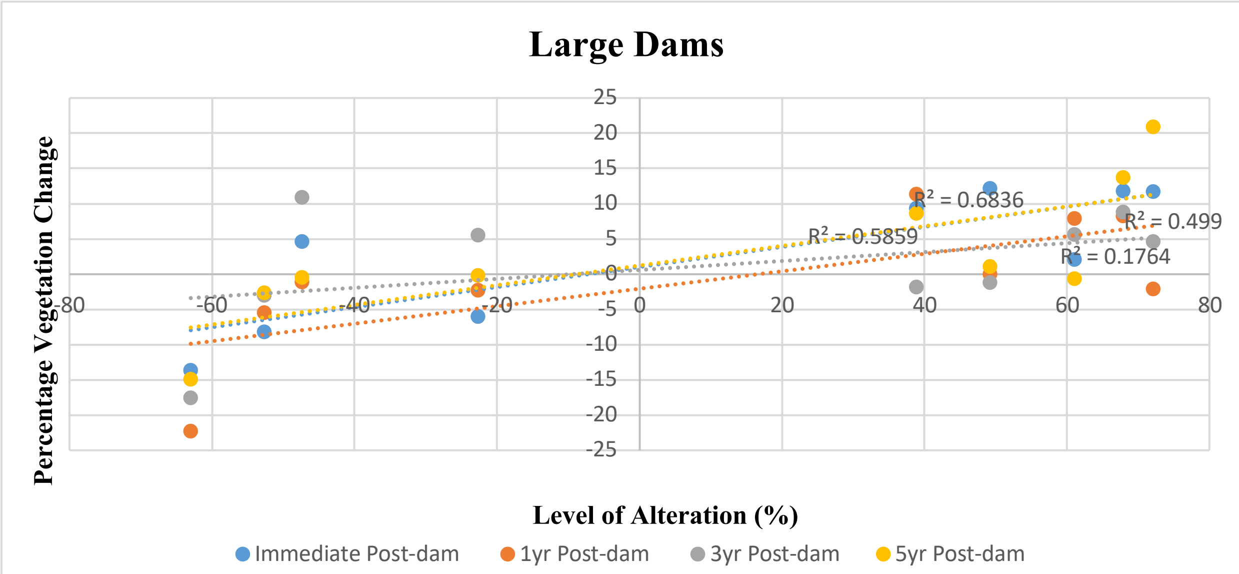


Figure 9. Correlations of flow regime changes to temporal changes of riparian vegetation cover

This correlation is a reflection of the best fit of the time span it takes for the riparian vegetation to respond to the changes in flow. The correlation analysis show that the '5-year post completion change' has the strongest fit (R^2=0.33) to flow regime change. In other words, the effects of the flow changes on the vegetation cover can be best expected after 5 years of the completion of the dam. It is however important to recognize that time of response of vegetation cover change also depends on the buffered region itself. Smaller dams which are built on lower order streams with smaller buffered areas are much more likely to show change effects than large capacity dams on higher order rivers with large buffered areas even though the levels of alterations in both cases are similar. The reason being that smaller areas are much more susceptible to change driven by the surrounding environment (topography and climate) than larger areas where these changes can be mitigated by other processes. Large dams (storage capacity above $3.7 * 10^7$ m^3 and power generation above 30 MW) are built on large rivers where large riparian buffers exist, and small dams (storage capacity below $3.7 * 10^7$ m^3 and power generation below 30 MW) are built where small buffers exist (Kibler and Tullos, 2013). Thus, the capacity of the dams was used as a proxy to riparian buffer zones, and the above analysis was sectionalized and performed on large dams and small dams separately (Figure 10; Table 4).



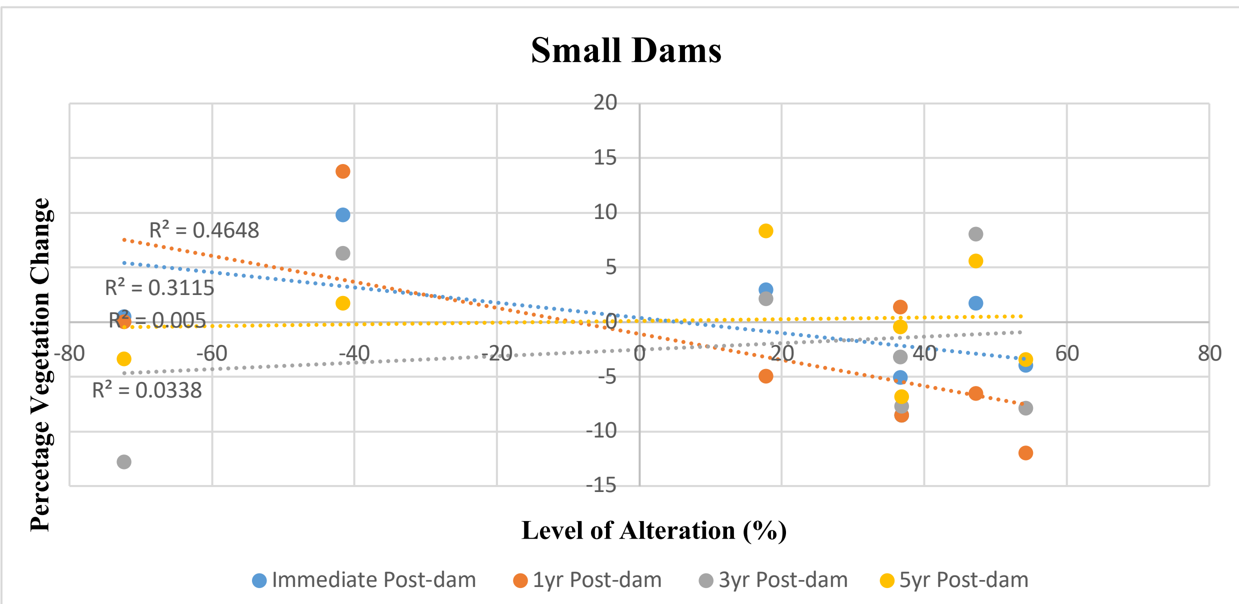


Figure 10. (a) Correlation for large dams (b) Correlation for small dams

Table 4. Summary of Coefficients of determination (R^2 values) for large and small dams

Temporal scale	Coefficient of Determination (R^2) values	
	Large Dams	Small Dams
post dam change	0.684	0.312
1yr post dam change	0.499	0.465
3yr post dam change	0.176	0.034
5yr post dam change	0.586	0.005

It was interesting to note the increment in the R^2 values in general in both the small and large dam categories. For small dams, the strongest correlation was immediately after the post-dam completion (R^2=0.46). For the larger dams the highest R^2 was 0.68. However, as discussed in section 4.3 this (R^2 value for large dams being highest immediately after the construction of the dam) is a result of the construction mechanism of larger dams as opposed to smaller ones and the vegetation change is not necessarily a reflection of flow regime changes due to dam operation. Thus, the best reflection of long-term flow alteration values is the 5-year post-dam completion vegetation changes (R^2=0.59). This leads to an inference of larger dams taking a considerably longer time to show the effects of alteration, whereas for smaller dams the effects are more immediate.

A further exploration of the relationship between flow alteration and downstream vegetation changes revealed complex intricacies. It was found that dam construction did not necessarily produce decreased flow regimes downstream and these regimes did not necessarily reduce riparian vegetation in the buffer. On the other hand, increased flow regimes also did not necessarily yield increased vegetation. A broad analysis of the relationships between the effects of river flow regime alteration on riparian vegetation change over time is presented in Table 5.

Table 5. Summary of relationship between river flow and vegetation cover change

Dam Index	Flow change	5-year average vegetation change	Trend of vegetation cover change
1	P	3.0	N
2	N	3.5	N
3	N	-4.8	P
4	P	2.1	P
5	N	-3.9	P
6	P	-6.8	P
7	P	-1.9	P
8	P	8.8	P
9	P	2.1	P
10	P	-7.9	P
11	N	7.8	N
12	P	6.8	N
13	P	10.7	P
14	N	-17.1	P
15	N	-0.7	P
16	P	3.7	N

Note: The 'Flow change' corresponds to the post-dam change of flow (increase/decrease in magnitude) while 'Average 5-year vegetation change' denotes the mean change in vegetation within a period of 5 years after the completion of the dam. Positive changes are denoted with a 'P' while negative changes are denoted with a 'N'.

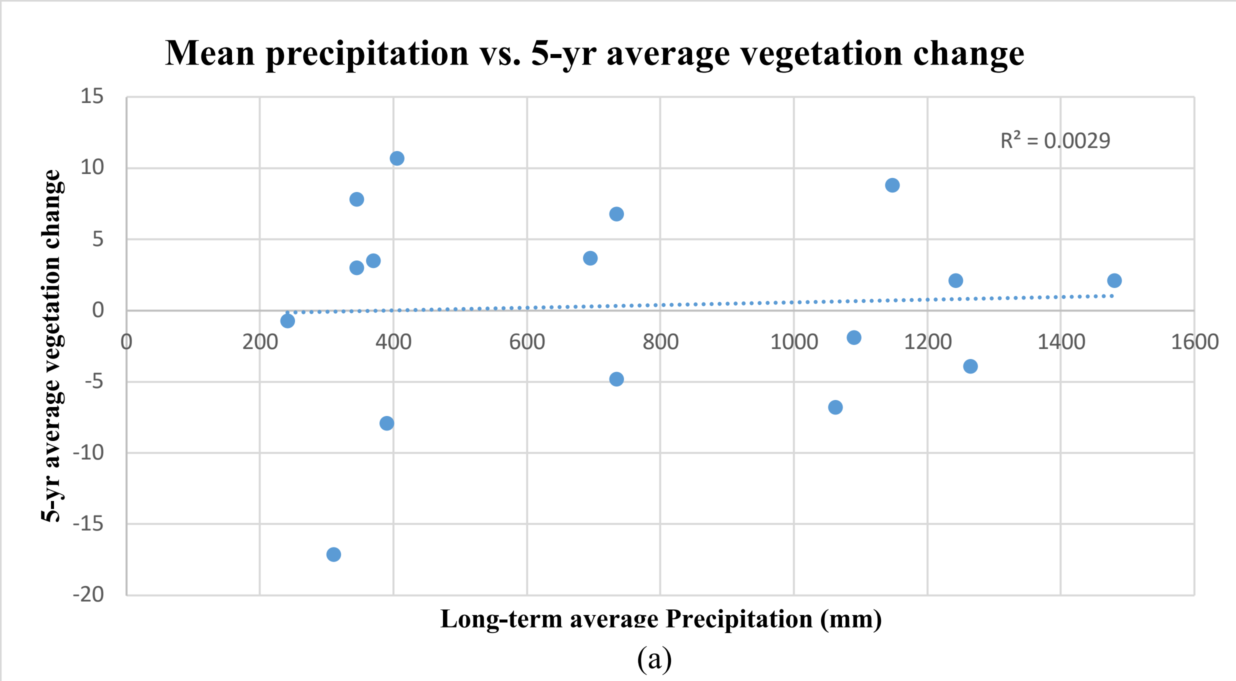
The 5-year average vegetation change recognizes increased or decreased post-dam vegetation status. 'Trend in vegetation change' reflects the temporal trend in the change of vegetation within the buffered region of each downstream dam location. There can be instances where mean change in vegetation records a positive value but the temporal trend is a negative one, or vice versa (e.g. Dam indices 1 and 2). The reasoning is that although a significantly large positive (negative) value at one temporal measurement (e.g. immediately after the construction of the dam) could govern the 5 year average the trend is determined by the remaining time stamps.

Results indicate that 10 of the 16 dam locations showed increased flow regimes post-dam construction while 6 exhibited decreased flows (Column 1 of Table 8). Out of the 10 increased regimes, however, only 7 showed a positive mean vegetation percentage over the 5-year time span considered. In other words, an increase in average vegetation over the 5-year time period was only shown in 7 locations. Only four of the 7 sites showed a positive trend in vegetation increase over time (following the color codes on Table 8: for a selected row, all 3 columns green). Three of the initial 10 locations which showed a negative mean vegetation percentage also depicted an increasing trend in vegetation over time which results in 7 of the initial 10 showing increasing trends in vegetation over time. This leads to the inference that most of the positive flow regime changes results in the continued growth of riparian vegetation and recovery of the riparian buffer over time.

Six of the 16 dam locations showed decreased flow regimes subsequent to dam-construction. Four of the 6 sites showed a negative average of riparian vegetation over the 5-year time period suggesting a decrease of vegetation compared to the pre-dam period within the riparian buffer. The 2 sites of the 6 which showed a positive average of riparian vegetation over the 5-year time period, in comparison, showed a decreasing trend in vegetation temporally.

As a whole, 11 of the 16 sites showed increasing trends in riparian vegetation over time (7 due to increased post-dam flows and 4 due to decreased flows). Five of the 16 locations showed decreasing trends (3 due to flow increases and 2 due to decreases). The reason for these mixed responses lie in the fact that although stream flow is one of the major factors that drive riparian vegetation change, it is not the only variable. The riparian zone is also determined by the regional climate and the geomorphological and disturbance regime (Naiman *et al*., 1993; Décamps *et al*., 1995; Shafroth *et al*., 2002). The differences in temperature and precipitation patterns over different regions trigger changes in the mean water vapor, precipitation patterns and evapotranspiration, which further leads to changes in ground water levels and soil moisture conditions which affects riparian vegetation growth (Su, 2012).

Thus, to better understand the effects of regional climate on the long-term recovery of these vegetative zones, the relationship of 5 year average post-dam vegetation change was regressed with long term precipitation and temperature averages (1971 to 2000; data obtained from https://www.ncdc.noaa.gov/) of the State the dam is located in (Figure 11). Although temperature was better correlated ($R^2 = 0.0178$) than precipitation ($R^2 = 0.0029$) as a whole both correlations, revealed a non-significant relationship of the effects of regional climate on the recovery of vegetation within buffered regions, for the given study sites.



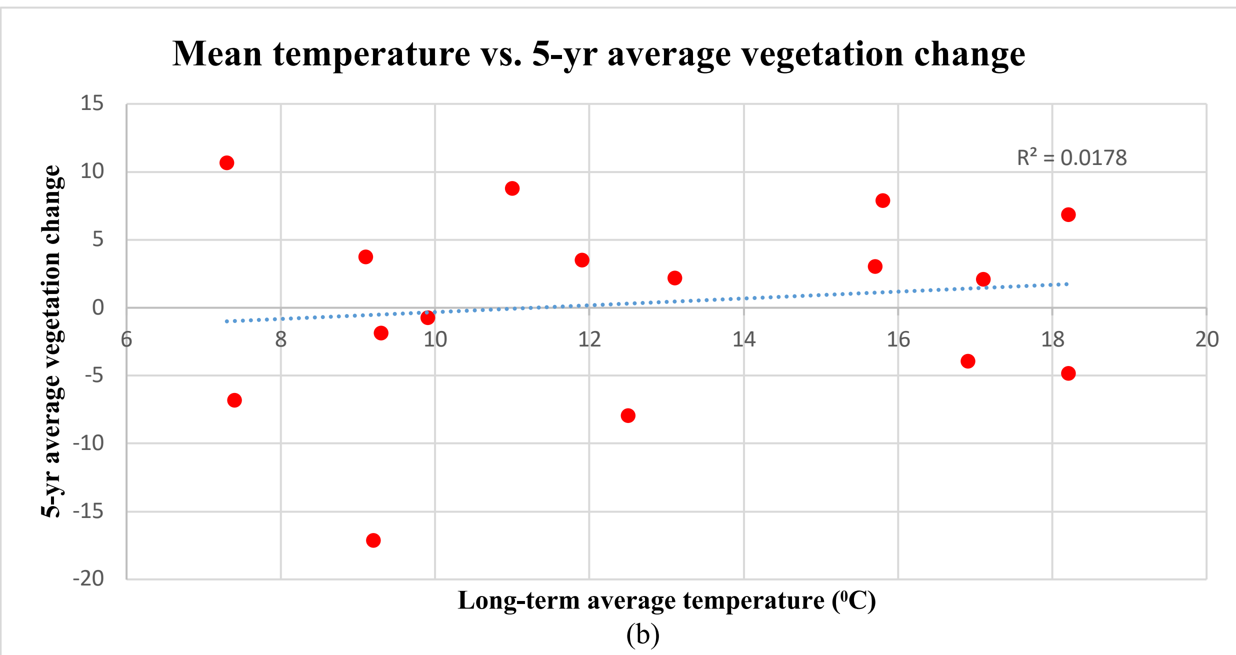


Figure 11. Correlation between States' (a) mean precipitations (b) mean temperatures against 5-yr average vegetation changes at each dam location

An attempt was made to develop a conceptual model that related the change of riparian vegetation to the temporal time scale of vegetation measurement, storage capacity of the dam, and the long-term average of temperature and precipitation of the dam location. This was attempted separately for small and large dams alike. The following was conceptualized:

$$V_c = K . T_v^{\propto} . S_c^{\beta} T_l^{\gamma} P_l^{\delta} \quad \text{..(2)}$$

where, V_c is change of Riparian vegetation, K is a constant governed by local geographical factors, $T_v^{\propto}$ is the temporal time stamp at which vegetation is measured, S_c^{β} is the storage capacity of the dam, T_l^{γ} is the long-term average temperature, and P_l^{δ} is the long-term average precipitation. However, analysis presented weak relationships ($R^2 < 0.08$) for both small and large dams alike. In order to develop a functioning robust relationship, in addition to the streamflow, knowledge on other salient geographical characteristics (i.e. topographical setting, soil properties, nutrient availability, fluvial disturbances) is needed warranting the need of further research and ecological modeling efforts to make better informed decisions.

CHAPTER 5

CONCLUSION

The influences of dam construction on hydrological regimes and their effects on the downstream riparian vegetation in 16 selected locations of the United States were studied using a combination of a holistic environmental flow approach (Range of Variability Approach - RVA) and remote sensing. The RVA was used to quantify the river flow paradigms of the selected locations before and after construction of dams, and the post-dam level of alterations. Of the 16 study locations assessed, 2 showed low levels of alteration, 11 moderate and 3 high levels of alteration.

Change detection of riparian vegetation cover revealed that at the majority of the sites (10 of the 16) riparian vegetation increased immediately after the construction of the dam. This counterintuitive result was attributed to the flow routing mechanism during the dam construction phase itself. Also, in a majority of the locations (10 of the 16) a decrease in vegetation was observed at the 1 year post-dam completion mark. Plant dieback and invasion of alien species was speculated as an explanation of this phenomenon. Recovery of the riparian zones was observed over time in 7 of the aforementioned 10 locations. As a whole, 11 of the 16 sites showed increasing trends in riparian vegetation over time.

Riparian zones below smaller dams showed effects of flow regime alterations at shorter time spans (1-year post-completion) than larger dams (5-year post completion). It was found that categorizing dams based on capacity was successful in understanding effects on the vegetation extents better. However, it was noted that flow regime changes did not directly coincide with changes in vegetation extents. In addition to the in-stream flow paradigm, regional climate, geomorphology and disturbance regime are identified as driving factors of riparian vegetation regulation. In order to set environmental flow recommendations, the need to have more specific knowledge of the expected ecological impacts is identified and the need for a multi-factor model that drives annual changes in riparian abundances is recognized in order to make better informed decisions on sustainable dam operations.

Future research could include integrating the effects of geomorphology (topography and fluvial disturbance regimes) into the analyses. An attempt will be made to apply a mechanistic model informed by the multiple regression analysis of this study’s sites to other uninformed sites to construct a policy-enabled model.

REFERENCES

Acreman, M., Arthington, A. H., Colloff, M. J., Couch, C., Crossman, N. D., Dyer, F., & Young, W. (2014). Environmental flows for natural, hybrid, and novel riverine ecosystems in a changing world. *Frontiers in Ecology and the Environment*, *12*(8), 466-473.

Alldredge, B., & Moore, G. (2014). Assessment of riparian vegetation sensitivity to river hydrology downstream of a major Texas dam. *River research and applications*, *30*(2), 230-244.

Anderson, T. W., & Darling, D.A. (1954). A test of goodness of fit. *Journal of the American statistical association*, *49*(268), 765-769.

Arthington, A. H., & Pusey B.J. (2003). Flow restoration and protection in Australian rivers. *River research and applications*, *19*(56), 377-395.

Auble, G. T., Friedman, J. M., & Scott, M.L. (1994). Relating riparian vegetation to present and future streamflows. *Ecological applications*, *4*(3), 544-554.

Beale, E. M., & Little, R. J. (1975). Missing values in multivariate analysis. *Journal of the Royal Statistical Society*. Series B (Methodological), 129-145.

Bunn, S. E., & Arthington, A.H. (2002). Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental management*, *30*(4): 492-507.

Castelle, A. J., Johnson, A. W., & Conolly, C. (1994). Wetland and stream buffer size requirements—a review. *Journal of Environmental Quality*, *23*(5), 878-882.

Congalton, R. G., Birch, K., Jones, R., & Schriever, J. (2002). Evaluating remotely sensed techniques for mapping riparian vegetation. *Computers and Electronics in Agriculture*, *37*(1), 113-126.

Davies, B. R., Thoms, M. C., Walker, K. F., O'keeffe, J. H., & Gore, J. A. (1994). Dryland rivers: their ecology, conservation and management. The Rivers Handbook: *Hydrological and Ecological Principles*, *2*, 484-511.

Décamps, H., Planty- Tabacchi, A. M., & Tabacchi, E. (1995). Changes in the hydrological regime and invasions by plant species along riparian systems of the Adour River, France. *River Research and Applications*, *11*(1), 23-33.

Dynesius, M., & Nilsson, C. (1994). Fragmentation and flow regulation of river systems in the northern third of the world. *Science*, 266(4)

Graf, W. L. (1999). Dam nation: A geographic census of American dams and their large- scale hydrologic impacts. *Water Resources Research*, *35*(4), 1305-1311Gregor, M. (2012). Surface-and groundwater quality changes in periods of water scarcity. Springer Science & Business Media.

Hart, D. D., & Finelli, C.M. (1999). Physical-biological coupling in streams: the pervasive effects of flow on benthic organisms. *Annual Review of Ecology and Systematics*, *30*(1), 363-395.

Hewitt, M. J. (1990). Synoptic inventory of riparian ecosystems: the utility of Landsat Thematic Mapper data. *Forest ecology and management*, *33*, 605-620.

Hu, W. W., Wang, G. X., Deng, W., & Li, S. N. (2008). The influence of dams on ecohydrological conditions in the Huaihe River basin, China. *Ecological Engineering*, *33*(3), 233-241.

Jensen, J. R., Rutchey, K., Koch, M. S., & Narumalani, S. (1995). Inland wetland change detection in the Everglades Water Conservation Area 2A using a time series of normalized remotely sensed data. *Photogrammetric Engineering and Remote Sensing*, *61*(2), 199-209.

Johansen, K., Coops, N. C., Gergel, S. E., & Stange, Y. (2007). Application of high spatial resolution satellite imagery for riparian and forest ecosystem classification. *Remote Sensing of Environment*, *110*(1), 29-44.

Junk, W. J., Bayley, P. B., & Sparks, R.E. (1989). The flood pulse concept in river-floodplain systems. *Canadian special publication of fisheries and aquatic sciences, 106*(1), 110-127.

Kibler, K. M., & Tullos, D.D. (2013). Cumulative biophysical impact of small and large hydropower development in Nu River, China. *Water Resources Research*, *49*(6), 1-15.

Klemas, V. (2011). Remote sensing of wetlands: case studies comparing practical techniques. *Journal of Coastal Research*, *27*(3), 418-427.

Klemas, V. (2014). Remote Sensing of Riparian and Wetland Buffers: An Overview. J*ournal of Coastal Research*, *30*(5), 869-880.

Makkeasorn, A., Chang, N. B., & Li, J. (2009). Seasonal change detection of riparian zones with remote sensing images and genetic programming in a semi-arid watershed. *Journal of Environmental Management*, *90*(2), 1069-1080.

Merritt, D. M., Scott, M. L., LeROY, P. O. F. F., Auble, G. T., & Lytle, D.A. (2010). Theory, methods and tools for determining environmental flows for riparian vegetation: riparian vegetation flow response guilds. *Freshwater Biology*, *55*(1), 206-225.

Naiman, R. J., Decamps, H., & Pollock, M. (1993). The role of riparian corridors in maintaining regional biodiversity. *Ecological applications*, *3*(2), 209-212.

Naiman, R. J., & Decamps, H. (1997). The ecology of interfaces: riparian zones. *Annual review of Ecology and Systematics*, *28*(1), 621-658.

Narumalani, S., Zhou, Y., & Jensen, J.R. (1997). Application of remote sensing and geographic information systems to the delineation and analysis of riparian buffer zones. *Aquatic Botany*, *58*(3), 393-409.

Nilsson, C., & Berggren, K. (2000). Alterations of Riparian Ecosystems Caused by River Regulation Dam operations have caused global-scale ecological changes in riparian ecosystems. How to protect river environments and human needs of rivers remains one of the most important questions of our time. *BioScience*, *50*(9), 783-792.

Nilsson, C., & Svedmark, M. (2002). Basic principles and ecological consequences of changing water regimes: riparian plant communities. *Environmental Management*, *30*(4), 468-480.

Poff, N. L., & Ward, J.V. (1990). Physical habitat template of lotic systems: recovery in the context of historical pattern of spatiotemporal heterogeneity. *Environmental Management, 14*(5), 629-645.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Brian, D. R., Richard, E. S., & Stromberg, J.C. (1997). The Natural Flow Regime. *Bio Science*, *47*(11), 769-784.

Poff, N. L., & Zimmerman, J.K. (2010). Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology*, *55*(1), 194-205.

Power, M. E., Sun, A., Parker, G., Dietrich, W. E., & Wootton, J. T. (1995). Hydraulic food-chain models. *BioScience*, *45*(3), 159-167.

Reiser, D. W., Wesche, T. A., & Estes, C. (1989). Status of instream flow legislation and practices in North America. *Fisheries*, *14*(2), 22-29.

Richardson, D. M., Holmes, P. M., Esler, K. J., Galatowitsch, S. M., Stromberg, J. C., Kirkman, S. P., & Hobbs, R. J. (2007). Riparian vegetation: degradation, alien plant invasions, and restoration prospects. *Diversity and distributions*, *13*(1), 126-139.

Richter, B. D., Baumgartner, J. V., Powell, J., & Braun, D.P. (1996). A method for Assessing Hydrologic Alteration within Ecosystems. *Conservation Biology*, *10*(4), 1163-1174.

Richter, B. D., Baumgartner, J. V., Wigington, R., & Braun, D.P. (1997). How much water does a river need? *Freshwater Biology, 37*(1), 231-249.

Richter, B. D., & Richter, H. E. (2000). Prescribing flood regimes to sustain riparian ecosystems along meandering rivers. *Conservation Biology*, *14*(5), 1467-1478.

Shafroth, P. B., Stromberg, J. C., & Patten, D.T. (2002). Riparian vegetation response to altered disturbance and stress regimes. *Ecological Applications*, *12*(1), 107-123.

Su, X., Zeng, B., Huang, W., Xu, S., & Lei, S. (2012). Effects of the Three Gorges Dam on preupland and preriparian drawdown zones vegetation in the upper watershed of the Yangtze River, PR China. *Ecological engineering*, *44*, 123-127.

Tharme, R. E. (2003). A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River research and applications*, *19*(5-6), 397-441.

TNC (The Nature Conservancy). (2009). Indicators of Hydrologic Alteration User's Manual.

U.S Department of Energy. (1996). Draft Environmental Impact Statement, Shutdown of the River Water System at the Savannah River Site, Aiken, South Carolina. Retrieved from http://books.google.com.

Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R., & Cushing, C.E. (1980). The river continuum concept. *Canadian journal of fisheries and aquatic sciences*, *37*(1): 130-137.

Walker, K. F., Sheldon, F., & Puckridge, J.T. (1995). A perspective on dryland river ecosystems. *River Research and Applications*, *11*(1), 85-104

Ward, J. V., and J. A. Stanford, 1987. The ecology of regulated streams: past accomplishments and directions for future research. In Regulated streams 391-409.

Warner, A.T., Bach, L.B., & Hickey, J.T. (2014). Restoring environmental flows through adaptive reservoir management: planning, science, and implementation through the Sustainable Rivers Project. *Hydrological Sciences Journal*, *59*(3–4), 770–785.

Yang, X. (2007). Integrated use of remote sensing and geographic information systems in riparian vegetation delineation and mapping. *International Journal of Remote Sensing*, *28*(2), 353-370.

Xie, Y., Sha, Z., & Yu, M. (2008). Remote sensing imagery in vegetation mapping: a review. *Journal of plant ecology*, *1*(1), 9-23.

APPENDIX A

Summary of mean absolute values of the 33 IHAs at the sixteen study sites

IHA Parameters	**Dam Index**															
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Group 1 Paramters																
October	0.55	0.78	0.37	0.27	1.47	1.27	0.30	1.67	0.73	0.71	0.31	0.89	1.33	1.12	0.20	1.40
November	0.58	1.15	0.81	0.19	1.47	1.19	0.30	1.67	1.33	0.42	0.22	1.00	1.33	1.11	0.77	1.40
December	0.69	1.22	0.36	0.21	1.47	1.34	0.21	1.48	1.00	0.46	0.27	1.00	1.33	1.10	0.42	0.64
January	0.03	1.40	0.99	0.27	1.47	1.27	0.24	1.67	1.00	0.93	-0.07	1.00	1.33	1.16	0.21	0.47
February	0.29	1.15	0.80	0.69	1.47	1.04	0.30	1.67	1.00	0.08	0.36	1.00	1.46	1.12	0.14	0.53
March	0.43	1.00	0.00	0.35	1.35	0.56	0.00	1.67	1.00	0.58	0.51	1.00	0.97	1.11	0.10	1.19
April	0.22	1.15	0.69	0.35	1.35	0.50	0.24	1.67	0.67	0.71	0.43	1.00	0.52	1.02	0.00	0.57
May	0.73	0.59	0.50	0.29	1.47	0.48	0.24	1.67	1.33	0.29	0.52	1.00	0.61	1.36	0.34	0.48
June	0.24	1.08	0.50	0.11	1.35	0.57	0.39	1.67	1.00	0.33	0.44	8.00	0.21	0.72	0.10	1.20
July	0.76	0.64	0.86	0.51	1.33	0.73	0.39	1.52	0.67	0.23	0.52	0.58	1.33	0.58	0.14	1.40
August	1.47	0.66	1.29	0.35	1.33	0.58	0.15	1.67	1.83	0.96	0.68	0.63	1.33	1.28	0.40	1.40
September	1.47	0.52	0.97	0.35	1.33	0.64	0.15	1.67	1.00	0.71	0.59	0.68	1.33	1.28	0.75	1.40
Group 2 Parameters																
1-day minimum	x	1.64	1.57	2.40	1.47	1.42	0.97	2.00	0.83	1.54	0.74	0.16	1.46	1.18	0.65	1.40
3-day minimum	x	1.14	1.57	0.61	1.47	1.34	0.97	2.00	0.67	0.58	1.35	0.16	1.33	1.19	0.58	1.40
7-day minimum	x	1.22	1.57	0.29	1.47	1.27	0.79	2.00	0.67	0.96	1.35	0.26	1.33	1.19	0.58	1.40
30-day minimum	0.11	1.07	1.38	0.11	1.47	1.19	0.48	1.67	1.00	0.71	0.85	0.47	1.33	1.20	0.56	1.40
90-day minimum	0.99	0.87	0.17	0.35	1.47	1.12	0.39	1.67	1.33	0.08	0.44	-3.50	1.33	1.11	0.40	1.40
1-day maximum	0.60	1.08	1.00	0.72	1.35	0.70	0.30	1.67	1.00	1.33	0.07	1.23	0.58	1.12	0.44	1.00
3-day maximum	0.64	0.87	0.90	0.19	1.22	0.56	0.42	1.67	1.00	0.67	0.11	1.23	0.58	1.03	0.22	0.60
7-day maximum	0.64	0.87	0.89	0.19	1.22	0.48	0.33	1.67	1.00	0.08	0.15	1.23	0.58	1.03	0.20	0.46
30-day maximum	0.66	1.01	0.79	0.35	1.35	0.62	0.30	1.67	1.00	0.08	0.18	1.23	0.24	1.03	0.14	0.45
90-day maximum	0.73	0.45	0.69	0.37	1.35	1.09	0.42	1.67	1.00	0.08	0.27	1.12	0.12	0.87	0.20	0.46

Number of zero days	0.81	1.28	1.38	1.93	0.00	0.00	0.00	0.33	0.80	0.19	1.53	1.33	0.00	0.00	0.00	0.00
Base flow index	0.00	1.22	1.05	0.61	0.68	0.15	0.97	2.00	1.00	0.96	1.35	0.26	1.33	1.20	0.92	1.40
Group 3 Parameters																
Date of minimum	-0.15	0.49	0.62	0.43	0.56	0.41	0.24	0.86	0.33	0.42	1.08	0.74	0.48	0.95	0.27	0.72
Date of maximum	0.50	0.57	0.41	0.26	0.17	0.39	0.15	0.71	0.71	0.21	0.23	0.70	0.79	0.83	0.47	0.24
Group 4 Parameters																
Low pulse count	x	0.38	0.71	0.67	0.44	1.34	0.49	1.67	1.11	0.96	1.33	xx	1.33	1.21	0.86	1.52
Low pulse duration	x	0.30	0.45	0.02	1.18	0.54	0.33	1.00	0.83	0.46	1.07	xx	1.00	0.87	0.26	1.00
High pulse count	1.57	1.26	1.03	0.47	1.63	0.65	0.20	1.67	1.02	1.21	0.47	1.04	0.61	1.03	0.54	0.65
High pulse duration	1.56	0.34	0.88	0.20	0.79	0.53	0.23	1.06	0.17	1.21	0.42	1.41	0.33	1.07	0.36	0.50
Group 5 Parameters																
Rise rate	0.41	1.16	0.65	0.29	1.47	0.41	0.15	1.52	1.33	0.71	0.40	1.53	1.18	1.18	0.51	0.66
Fall rate	1.38	1.14	0.90	0.19	1.75	0.57	0.15	1.00	1.42	0.42	1.11	1.53	1.44	1.69	1.92	0.72
Number of reversals	0.94	1.01	0.46	0.05	1.20	0.41	0.12	1.48	0.67	1.21	0.40	0.00	1.17	0.20	0.29	0.17
Average Degree of HA	0.67	0.93	0.83	0.44	1.23	0.77	0.34	1.53	0.95	0.62	0.60	0.97	0.96	1.03	0.42	0.90
Scaled Average	49.21	47.37	52.62	17.75	72.30	54.19	36.62	72.05	47.21	36.82	41.56	38.83	67.83	62.98	22.69	60.99
Flow regime change	P	N	N	P	N	P	P	P	P	P	N	P	P	N	N	P
Level of alteration	M	M	M	L	H	M	M	H	M	M	M	M	H	M	L	M

Note: Flow Regime Changes: Positive = **P**; Negative = **N**
Level of Alteration: Low = **L**; Moderate: **M;** High = **H**

APPENDIX B

IHA non-parametric RVA scorecard results for the L-lake Dam

IHA Parameter	Pre-Dam Medians	Coeff. of Dispersion	Post-dam Medians	Coeff. of Dispersion	Absolute mean degree of alteration	Level of Alteration (%)
Parameter Group #1						
October	64	0.9609	1.7	1.779	1.47	83.81
November	74	1.061	1.65	1.22	1.47	83.81
December	68	1.015	1.85	1.095	1.47	83.81
January	88	1.159	2.3	0.9565	1.47	83.81
February	88	0.7585	2.4	1.297	1.47	83.81
March	88	2.222	1.9	2.434	1.35	76.88
April	82.5	2.555	1.525	5.492	1.35	76.88
May	75	1.973	1.5	2.767	1.47	83.81
June	78	2.144	1.475	2.653	1.35	76.88
July	68	1.228	1.5	3.842	1.33	75.72
August	62	0.9274	1.35	1.837	1.33	75.72
September	69	0.9094	1.35	2.259	1.33	75.72
Parameter Group #2						
1-day minimum	17	1.276	0.855	0.4064	1.47	83.81
3-day minimum	19	1.437	0.9967	0.4214	1.47	83.81
7-day minimum	31.86	1.14	1.086	0.4418	1.47	83.81
30-day minimum	54.12	0.935	1.162	0.4736	1.47	83.81
90-day minimum	73.93	0.9993	1.357	1.108	1.47	83.81
1-day maximum	341	0.8695	27.5	2.836	1.35	76.88
3-day maximum	246.7	1.17	26	3.155	1.22	69.93
7-day maximum	225.1	1.195	20.31	3.772	1.22	69.93
30-day maximum	113.2	1.772	11.78	3.992	1.35	76.88
90-day maximum	104.3	1.414	11.02	1.705	1.35	76.88
Number of zero days	0	0	0	0	0.00	0.00
Base flow index	0.3559	0.6751	0.2613	1.611	0.68	38.78
Parameter Group #3						
Date of minimum	250	0.2022	216	0.3408	0.56	31.84
Date of maximum	69	0.4536	198	0.4693	0.17	9.80
Parameter Group #4						
Low pulse count	1	9.5	0.5	5.5	0.44	24.90
Low pulse duration	8	1.047	64	8.637	1.18	67.24
High pulse count	5	1.3	1	1.6	1.63	92.91
High pulse duration	3	3.125	3	1	0.79	45.34
Parameter Group #5						
Rise rate	4	0.6875	0.25	2.35	1.47	83.81
Fall rate	-3	-0.75	-0.15	-0.9167	1.75	100.00
Number of reversals	110	0.1182	93.5	0.2193	1.20	68.78

APPENDIX C

IHA non-parametric RVA scorecard results for the Stonewall Jackson Dam

IHA Parameter	Pre-Dam Medians	Coeff. of Dispersion	Post-dam Medians	Coeff. of Dispersion	Absolute mean degree of alteration	Level of Alteration (%)
Parameter Group #1						
October	8.8	1.938	85	0.6971	1.67	80.00
November	27.25	1.046	127	1.484	1.67	80.00
December	35.5	0.9296	226.5	1.232	1.48	68.57
January	36.5	1.226	246	1.574	1.67	80.00
February	55.75	0.4081	338	1.634	1.67	80.00
March	56.5	0.2876	519.5	1.079	1.67	80.00
April	42.5	0.7735	325.3	1.043	1.67	80.00
May	22	1.518	161.5	2.161	1.67	80.00
June	2.775	7.691	107.5	0.7256	1.67	80.00
July	3.15	4.221	107.5	0.4605	1.52	71.42
August	2.6	4.961	106	1.012	1.67	80.00
September	2.825	2.589	97.5	0.4038	1.67	80.00
Parameter Group #2						
1-day minimum	0.035	21.29	38.5	0.6481	2.00	100.00
3-day minimum	0.045	17.85	43.5	0.6575	2.00	100.00
7-day minimum	0.07929	11.64	51	0.5088	2.00	100.00
30-day minimum	0.8435	5.156	71.05	0.451	1.67	80.00
90-day minimum	10.55	2.082	113.7	0.4793	1.67	80.00
1-day maximum	739.5	0.717	2425	0.7062	1.67	80.00
3-day maximum	467.2	0.5118	1737	0.535	1.67	80.00
7-day maximum	305.8	0.466	1304	0.3355	1.67	80.00
30-day maximum	134.9	0.7567	717.7	0.7411	1.67	80.00
90-day maximum	94.29	0.5803	502.1	0.5784	1.67	80.00
Number of zero days	4	5.188	0	0	0.33	0.00
Base flow index	0.001522	10.77	0.1499	0.5725	2.00	100.00
Parameter Group #3						
Date of minimum	240	0.2534	179.5	0.3948	0.86	31.42
Date of maximum	337.5	0.3627	65	0.3231	0.71	22.86
Parameter Group #4						
Low pulse count	6.5	0.5385	0	0	1.67	80.00
Low pulse duration	5.5	2.432	x	x	1.00	40.00
High pulse count	18.5	0.3243	2	3.125	1.67	80.00
High pulse duration	4	0.1875	105.3	4.239	1.06	43.43
Parameter Group #5						
Rise rate	6.275	0.6536	22.25	0.8652	1.52	71.42
Fall rate	-3.75	-0.8	-21	-0.7976	1.00	40.00
Number of reversals	105	0.2548	130	0.09038	1.48	68.57

APPENDIX D

IHA non-parametric RVA scorecard results for the Ritschard Dam

IHA Parameter	Pre-Dam Medians	Coeff. of Dispersion	Post-dam Medians	Coeff. of Dispersion	Absolute mean degree of alteration	Level of Alteration (%)
Parameter Group #1						
October	6.3	0.87	26	1.39	1.33	91.43
November	7.7	0.47	21.25	0.24	1.33	91.43
December	8.1	0.49	20	0.24	1.33	91.43
January	8.3	0.73	20.5	0.26	1.33	91.43
February	8.4	0.73	20.5	0.40	1.46	100.00
March	12	1.65	21.5	0.40	0.97	66.50
April	68	0.88	28.5	1.67	0.52	35.32
May	310	0.85	122	2.57	0.61	41.56
June	82	2.01	119.8	1.62	0.21	14.55
July	12	0.93	65	0.72	1.33	91.43
August	7.1	1.07	106.5	0.65	1.33	91.43
September	6	0.81	100	0.85	1.33	91.43
Parameter Group #2						
1-day minimum	2.8	0.89	15	0.35	1.46	100.00
3-day minimum	2.8	0.88	15	0.33	1.33	91.43
7-day minimum	3.2	0.73	15	0.35	1.33	91.43
30-day minimum	4.13	0.67	19.22	0.33	1.33	91.43
90-day minimum	7.203	0.57	19.85	0.29	1.33	91.43
1-day maximum	634	0.44	664.5	0.93	0.58	39.48
3-day maximum	591.7	0.42	648.7	0.91	0.58	39.48
7-day maximum	541.1	0.38	612.9	0.81	0.58	39.48
30-day maximum	425.5	0.48	357.3	0.98	0.24	16.62
90-day maximum	203.4	0.56	190.8	0.89	0.12	8.31
Number of zero days	0	0.00	0	0.00	0.00	0.00
Base flow index	0.04803	0.48	0.212	0.66	1.33	91.43
Parameter Group #3						
Date of minimum	259	0.10	311	0.33	0.48	33.25
Date of maximum	139	0.05	156	0.32	0.79	54.50
Parameter Group #4						
Low pulse count	4	1.00	0	0.00	1.33	91.43
Low pulse duration	6.75	1.82			1.00	68.57
High pulse count	2	1.50	4	0.88	0.61	41.56
High pulse duration	36.75	1.97	16.5	5.44	0.33	22.73
Parameter Group #5						
Rise rate	0.9	1.00	3	0.71	1.18	81.07
Fall rate	-1.1	-1.00	-3.5	-0.75	1.44	99.00
Number of reversals	84	0.37	59.5	0.18	1.17	80.09

APPENDIX E

Coordinates of dams and high resolution Google imagery of locations (accessed 19 Oct. 2017)

Dam Index	Dam Name	River	State	Latitude	Longitude
1	New River Dam	New River	AZ	33.735000	-112.228610
2	Brantley Dam	Pecos River	NM	32.544168	-104.380917
3	Simon Freese Dam	Colorado River	TX	31.496700	-99.6683000
4	Oliver Lock and Dam	Black Warrior	AL	33.208797	-87.5926920
5	L Lake Dam	Steel Cr, Savannah River	SC	33.160000	-81.6322000
6	Kent Falls Dam	Saranac River	NY	44.701900	-73.6053000
7	Grays Landing Lock and Dam	Monongahela River	PA	39.783330	-79.9166700
8	Stonewall Jackson Dam	West Fork	WV	39.000000	-80.4733300
9	Nolin River Fork Dam	North Fork Nolin River	KY	37.276742	-86.2467840
10	Longview Dam	Little Blue River	MO	38.898245	-94.4485200
11	Lee Creek Dam	Lee Cr, Arkansas River	AR	35.484700	-94.3928000
12	Palo Duro Dam	Palo Duro Creek	TX	36.361700	-101.163300
13	Ritschard Dam	Muddy Creek	CO	40.112806	-106.415458
14	Bor Jordanelle Dam	Provo River	UT	40.596670	-111.423330
15	South Fork Dam	South Fork Humboldt River	NV	40.682975	-115.784962
16	Galesville Dam	Cow Cr, Umpqua River	OR	42.849000	-123.178800

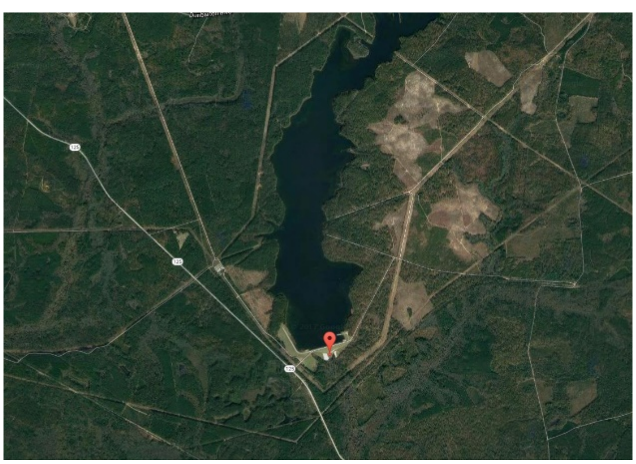
(1) New River Dam

(2) Brantley Dam

(3) Simon Freese Dam

(4) Oliver Lock and Dam

(6) Kent Falls Dam



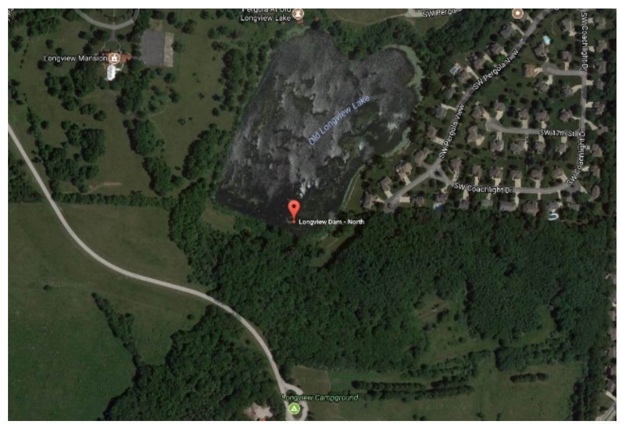
(5) L Lake Dam

(7) Grays Landing Lock and Dam

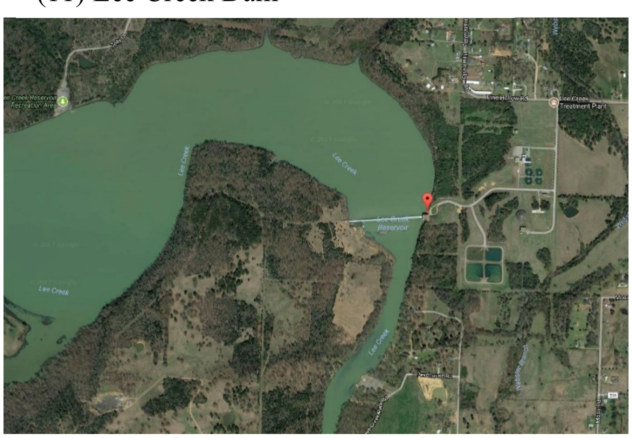
(8) Stonewall Jackson Dam

(9) Nolin River Fork Dam

(10) Longview Dam



(11) Lee Creek Dam



(12) Palo Duro Dam

(13) Ritschard Dam

(14) Bor Jordanelle Dam

(15) South Fork Dam

(16) Galesville Dam