

**Impacts of Beetle Kill on Modeled Streamflow Response in the
North Platte River Basin**

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Master of Science
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Jordan Andrew Rudolph
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Dedication

I would like to dedicate this thesis to my parents, Regina L. & Glynn A. Rudolph, for always pushing me to perform my best in everything I do in life. I could not have been given better role models to guide me down the path to success. I would like to eternally thank you both for everything you have, are, and will do for me the rest of my life. I am truly grateful to have a set of parents that love one another and who would go out of their way for anything that Jared or I would ever need. I would not be where I am today without you both and I would like you to know that I love you both with all my heart. I am thankful to God everyday that I have you both as my parents; it is honestly a pleasure to be your son and I hope that one day, I will be able to give back to you more in return than you ever gave me. I would also like to dedicate this thesis to my brother, Jared A. Rudolph, with whom I have always had a “love-hate” relationship. I regret that I have not been able to be as supportive to you growing up through high school as I would have liked, due to my collegiate career, but I find enjoyment in the thought that we will soon be closer than you ever know as we grow old and have families of our own. I would like you to know that I will always be supportive in whatever you decide to do in life and if you ever need help, I will always be there for you. I mean, you are my one and only brother, and I want you to know that I want the best for you in everything you do in life. I would also like to dedicate this thesis to my future spouse, Mary Roxana “Roxy” Nahhas for always being by my side and supporting me throughout my collegiate career. We have been down a rocky road the past couple of years, but I can honestly say that we made it because of our love for one another. I know we do not see

eye to eye on every issue, but we have a relationship that enables us to effectively communicate with one another to resolve our problems. I miss all the times we had when we were both undergraduates at UT and going to your sorority date parties, but I know there are many more memorable times still to come. I look forward to you graduating law school from Memphis, getting married, and then settling down and starting a family. I sincerely cannot wait until we are able to start our lives together! I would also like to also dedicate this thesis, to my aunt and uncle, Myrna M. & Archie B. Van Buskirk, for always being by my side and supporting me throughout my life. Both of you have been like another set of parents to Jared and I by always being so involved in our lives. I know that, just like my parents, you have given up so much of your time and effort for us that I would like to recognize you for this. Thank you both for giving me guidance, support, and encouragement throughout my youth; your influence in my life has played an important role in shaping me into the man that I am today. Last, but certainly not least, I would like to dedicate this thesis to my belated grandmother, Mildred L. Loesch, who taught me how to be a gentleman and the utmost importance of keeping God our Father and the Lord Jesus Christ first in my life. I was very sadden to see her have to leave this earth so soon in my life, but I find enlightenment in the fact that I know she is in Heaven right now watching over our family and raining down her blessings. I would like to thank you all again for being so loving and supportive of me in everything that I have and will continue to do in my life; I am truly blessed.

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Abstract

A beetle epidemic has been sweeping its way across the western United States and into portions of southern Canada that has caused millions of acres of forests to ultimately die. This beetle outbreak, that many have come to know simply as “beetle kill”, has caused many scientists to feel that such dramatic changes in land cover could potentially alter the hydrology throughout much of the West. One of the most important hydrological processes that beetle kill has the potential to impact is streamflow. This paper attempts to evaluate the hydrological impacts on streamflow from land cover change due to beetle kill in the North Platte River Basin (NPRB), by utilizing a hydrological model, Variable Infiltration Capacity (VIC). VIC is a land surface hydrological model that, for this analysis, has been calibrated and validated for the periods of 1950-1980 and 1981-2000, respectively, by using daily meteorological forcings and monthly streamflow data. In order to quantify the impacts on streamflow, land cover was changed by decreasing forest canopy coverage in order to mimic beetle kill for five different simulations, based on results obtained from basin level estimates of canopy loss, with error, using remote sensed data. Based on these five simulations, an increase of approximately 1% to 10% in decadal streamflow was observed for a decrease of 16% to 40% in forested land cover. Additionally, the average change in forest cover of 28% produced an increase in decadal streamflow of roughly 5%. However, based on model limitations and general assumptions, this estimate of increased streamflow was likely a high estimate. Given beetle kill did not fully manifest itself in the NPRB until roughly 2007/2008, modeling the proposed changes in land cover for the period 1950-

2000 was performed in order to see the possible implications beetle kill would have had in the past. By doing so, the results could then be applied to the present day to try and predict what effects beetle kill could have in the future.

Table of Contents

Chapter 1.....	1
Introduction.....	1
Process of Tree Infection from Beetle Kill.....	3
Causes for Concern	4
Chapter 2.....	7
Study Area	7
Maximum Likelihood Classification.....	10
Hydrologic Model	11
Data Description.....	14
NAIP Imagery Data	14
VIC Model Data	17
Model Simulations	19
Scenario: Decrease Forest Cover to Emulate Beetle Kill	22
Hypothesis & Uncertainty	26
Chapter 3.....	29
Land Cover Classification Results	29
VIC Results.....	30
Model Calibration and Validation.....	30
Scenario: Streamflow Response Due to Land Cover Change.....	35
Chapter 4.....	47
Conclusions.....	47
List of References.....	49
Vita	54

List of Tables

Table 1. VIC vegetation reference index.	18
Table 2. Cumulative yearly streamflow volumes for each decadal period.	42
Table 3. Percent increase in decadal streamflow for change in land cover simulations.	43
Table 4. Numerical increase in decadal streamflow for change in land cover simulations	43

List of Figures

Figure 1. Location map	9
Figure 2. NAIP imagery classification for pre-beetle kill and post-beetle kill	16
Figure 3. Gridded map with forested grid cells highlighted	24
Figure 4. VIC model calibration plot and scatter plot for 1950-1980.	33
Figure 5. VIC model validation plot and scatter plot for 1981-2000	34
Figure 6. Gaussian distribution of land cover classification with 95% confidence level.....	37
Figure 7. Cumulative yearly streamflow volumes for the period of 1950-2000.....	38
Figure 8. Cumulative yearly streamflow volumes for each decadal period.....	41

Chapter 1

Introduction and Literature Review

Introduction

Many coniferous forests across western North America are experiencing a vast epidemic of bark beetles that has caused widespread tree mortality to peak to surprisingly unprecedented levels. The current epidemic, which began in North America roughly around the mid to late 1990s, has claimed billions of trees ranging from parts of northern Mexico all the way to the southern Canadian provinces of Alberta and British Columbia (Bentz & Nordhaus, 2009; Bentz et al., 2010; Kenarsari & Zheng, 2011). Since its beginning in the United States, this outbreak of bark beetles has ultimately equvalated into roughly 42 million acres of affected forests, which compares closely in magnitude to the entire state of Oregon (U.S. Forest Service, 2011). The widespread pandemic has become so extensive throughout much of the West, that many locals have coined the phrase of “beetle kill” to describe the process the bark beetles employ to kill off the trees and eventually, given the appropriate amount of time, entire stands of forests. Since beetle kill has become a major problem in such a short period of time, many researchers have come to realize that such large scale tree mortality could have implications on the water resources of many beetle infested forest regions (Grainger & Bates, 2010; Lukas & Gordon, 2010; Maloney, 2005; Pugh & Gordon, 2012).

Of all the regions severely affected by beetle kill across western North America, no area has been more greatly affected than northern Colorado and southern Wyoming (Pendall et al., 2010; Robbins, 2008). Since the late 1990s, the combined amount of

coniferous forests affected by the entire species of bark beetle in the states of Colorado and Wyoming have totaled to approximately 10 million acres of forested land cover (U.S. Forest Service, 2011). The particular species of bark beetle that is causing so much devastation throughout much of the Rocky Mountain region is the mountain pine beetle (MPB) (*Dendroctonus ponderosae*) (Logan & Powell, 2001; Powell & Bentz, 2009; Samman & Logan, 2000). It has been estimated that since 2008, in the states of Colorado and Wyoming, the MPB has affected nearly 5 million acres of lodgepole pine forest alone; this is an increase of roughly 25 million trees from the baseline year of 2006, in which only 2.6 million trees were infected (Ballantyne, Fernandez, Neff, Gaston, & Scarlata, 2009).

Although the MPB has caused a great deal of devastation to forests throughout much of the West, MPBs have always been a native species to the pine forests of western North America. According to historical records from the past century, outbreaks of MPB have always occurred throughout the West but never to the extent to which levels are currently being observed (Bentz & Nordhaus, 2009; Bentz et al., 2010; Powell & Bentz, 2009; Regniere & Bentz, 2009). MBPs, and in general the entire species of bark beetle, have always played an important role in maintaining a healthy, functioning forest ecosystem by killing off stressed trees that have been affected by other natural processes such as lightning strikes, wild fires, wind storms, etc. (Logan & Powell, 2001). When bark beetles are allowed to successfully remove defective trees from a forest stand, it eventually promotes the growth of smaller saplings in the understory of the forest to begin the process of forest regeneration (Pugh & Gordon, 2012). The recent problem that

has caused this beetle kill epidemic to spiral so far out of control is the result of massive swarms of beetles attacking completely healthy trees. Many scientists have speculated that the underlying cause for the massive beetle outbreak can be largely linked to climate change and other associated abiotic factors (Bentz et al., 2010; Powell & Bentz, 2009; Pugh & Gordon, 2012; Regniere & Bentz, 2007, 2009).

For the most part, around the world, there has been a general trend of increasing temperatures. In the western United States, mean annual temperatures have increased by 3.5°F since 1984 across all latitudes (IPCC, 2007). Since temperatures have continued to increase around the globe, many bark beetles, specifically MPBs, have been given the opportunity to move into higher latitudes and altitudes than ever previously recorded (Bentz & Nordhaus, 2009; Bentz et al., 2010). Scientists have concluded that the combination of a decade of drought has weakened trees, warmer winters have exponentially increased beetle populations, and dense, overgrown, homogeneous forests have all amalgamated to trigger this historic beetle outbreak, thus enabling it to reach epic proportions (Bentz et al., 2010; Lukas & Gordon, 2010; Mishra et al., 2010; Pugh & Gordon, 2012; Samman & Logan, 2000).

Process of Tree Infection from Beetle Kill

A tree initially becomes infected when a single bark beetle of the genus *Dendroctonus*, bores a hole into the bark of a mature pine tree. As the beetle begins digging a gallery into the bark of the tree, in which to lay its eggs, the tree senses an attack and goes on the defensive by naturally excreting a white resin in hopes of flushing

out the beetle (Amman & Cole, 1983; Lieutier, 2002). When the beetle realizes the tree's attack, the beetle goes on a counter attack of its own by releasing a pheromone into the air that alerts nearby beetles to join in on the attack of the tree (Robbins, 2008). As more and more beetles continue their attack on the tree they inadvertently introduce a fungus to the tree known as the blue stain fungus (Samman & Logan, 2000). This blue stain fungus can be easily identified in many tree species because of the effect that it has on both the color change of the inner bark and the effect that it has at stopping the release of resin to fend off the beetles. The fungus works by clogging up the xylem (resin) cells which significantly reduce the tree's transpiration rates within the first few weeks and eventually ending it completely within a year of infestation (Lukas & Gordon, 2010; Pendall et al., 2010). During the process of the attack, the eggs eventually start to hatch and the larvae begin to feed on the rich, sweet cambium layer of the phloem (inner bark) within the tree. As the larvae feed, they start to interrupt the flow of nutrients from the root system to the upper canopy of the tree. Ultimately, the combination of the feeding beetles carrying the blue stain fungus and the larvae interrupting the flow of nutrients throughout the tree, eventually coalesce to suffocate the tree until death is inevitable within about a year depending on the tree species (Samman & Logan, 2000).

Causes for Concern

One of the most obvious effects that have and will continue to come from beetle kill is the constant threat of falling trees. Depending on the speciation of the affected trees, most will begin to fall within 5-15 years of infestation (Pugh & Gordon, 2012).

Falling trees such as this can cause a major risk to humans and infrastructure. In many places throughout Colorado and Wyoming, numerous campgrounds, parks, and trails have been closed to the public along with miles of roadways and power lines which have had to be cleared because of the ever looming threat of falling timber (Robbins, 2008; U.S. Forest Service, 2011). However, by far the biggest threat that face the remaining “alive” forests of the American west are the serve threat of catastrophic wild fires due to falling timber. In the upcoming years, there will be millions of dead trees that will begin to fall to the ground, thus creating a potential heavy fuel loading for many wild fires to take place (Logan & Powell, 2001).

Other potential causes for concern are for the many animals that live in the affected beetle killed regions. Because there have been so many trees killed due to beetle kill, numerous animals have had to deal with shifting ecosystems (Samman & Logan, 2000). The more forests that are lost due to beetle kill dramatically increases the chances for flash floods throughout the West because there are no longer any trees in place to catch the snow and attenuate the snow melt (Pugh & Gordon, 2012). Flash floods create the possibility of more stream bank erosion, which decreases water quality by introducing more sediments into streams (Grainger & Bates, 2010). Flash floods can greatly impact certain aquatic species such as salmon by causing injury and destroying habitats and/or simultaneously causing suffocation to occur by clogging up gills from increased sediment loading. In addition, as trees continue to die and eventually begin to fall, the potential for events such as mudslides start to increase due to the decrease in ground stability from the decaying root systems of the infected trees (Robbins, 2008; Samman & Logan, 2000).

Another important issue that has arisen due to the beetle kill epidemic, which has caused a great deal of concern, is for the stability of the tourism industry. Approximately 4 million people visit the West for sightseeing and recreation purposes each year (Flint, Qin, & Daab, 2008; Robbins, 2008). Because of the quick progression of beetle kill over the past decade, there has been a very dramatic change in the scenery, due to the massive number of dying forests, which many park officials feel could cause a significant impact on the tourism industry (U.S. Forest Service, 2011). In addition to this, many skiing resorts have been greatly impacted as well, due primarily from the risk of the large number of falling trees. Numerous skiing facilities have had to budget for cutting down and/or removing infected trees from the mountainside and in addition, have had to replant smaller saplings in order to maintain slope stability (Samman & Logan, 2000). Not only has the beetle epidemic affected the tourism industry out West, but it has also affected many individual home owners as well. According to Flint et al. (2008), roughly 90% of people surveyed following a bark beetle outbreak in Colorado indicated that they had experienced costly tree clearing expenditures.

Chapter 2

Methodology

Study Area

The area of study is the North Platte River Basin (NPRB), which is located in the states of northern Colorado and southern Wyoming at latitudes $40^{\circ}18'45''$ to $41^{\circ}56'15''$ N and longitudes $105^{\circ}56'15''$ to $107^{\circ}3'45''$ W (Figure 1). The location of the NPRB lies between the Sierra Madre range to the west and the Medicine Bow range to the east. Both of these mountain ranges compose part of the boundary for the easterly and westerly portions of the basin. Any precipitation that becomes surface runoff is diverted into waterways which flow to lower elevations within the basin and eventually become streamflow that can be measured at United States Geological Survey (USGS) streamflow gage 06630000, which is located above Seminoe Reservoir, the first in a series of impoundments in the state of Wyoming. The annual precipitation for the NPRB varies from approximately 25-60 inches with 40-70% as precipitation in the form of snow (WWDC, 2005). The NPRB currently contains eight SNOTEL stations and six USGS streamflow gages, which are continuously being operated and monitored by the Natural Resource Conservation Service (NRCS) and the United States Geological Survey (USGS), respectively. The primary body of water that runs through the basin is the North Platte River, which is a tributary of the Platte River and originates in the higher elevations of northern Colorado. The river flows northward into Wyoming along the westward side of the Medicine Bow range and finally culminates with the Medicine Bow River, which ultimately empties into the Seminoe Reservoir. Nearly all of the water in the

form of streamflow from the NPRB's riparian system is channeled through the Seminoe Reservoir which is located in Carbon County, Wyoming. The NPRB has a drainage area of approximately 4175 mi² of which a total of 30% or 1250 mi² is forested land cover. The watershed has an elevation range from roughly 12000 ft to 6400 ft, with varying terrain consisting from rugged mountains to gently sloping grasslands. Of all the macro-scale watersheds in the Colorado/Wyoming region, the NPRB is one of the most severely affected by the recent beetle kill infestation. Presently, the NPRB, which was severely hit with the MPB epidemic in 2007/2008, has seen virtually all the lodgepole pine forests completely annihilated by beetle kill (Pendall et al., 2010).

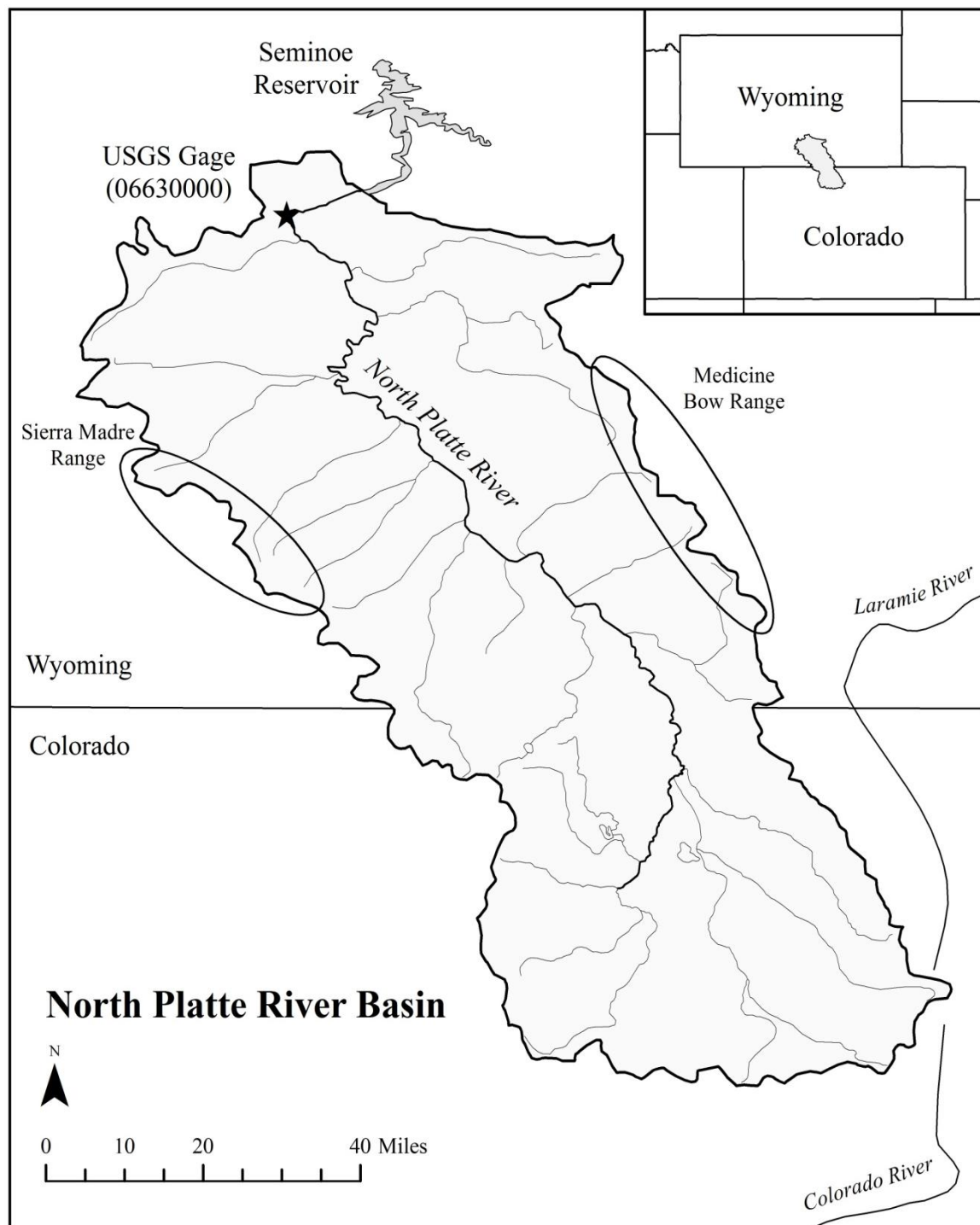


Figure 1. Location map of the North Platte River Basin, with major areas for weather modification operations, rivers, and USGS streamflow gage 06630000 (indicated by star) labeled.

Maximum Likelihood Classification

The accuracy of classification results is determined by which classification method is selected. Generally, landscapes with homogeneous spectral responses are estimated through a multivariate Gaussian distribution and the assignment of pixels to classes is often based on a maximum likelihood classification (MLC) (Richards, 2012). Of all the parametric classification techniques, MLC is the most commonly used for classification of forest landscapes (Hubert-Moy, Cotonnec, Le Du, Chardin, & Perez, 2001). Being consistent with previous literature, a MLC technique is used to classify forest cover using the interactive supervised classification tool in ESRI's ArcGIS 10.0. This tool uses an MLC algorithm to classify imagery based on a signature file created from user derived training samples. The MLC algorithm is based on two principles; the cells in each class sample in the multidimensional space follow a Gaussian distribution and Bayes' theorem of decision making (Richards, 2012).

The MLC computes a variance-covariance matrix for each of the class signatures when assigning each pixel to one of the classes represented in the signature file. Under the assumption of normality a class sample can be characterized by the mean vector and the variance-covariance matrix (Lillesand, Kiefer, & Chipman, 2004). Given these two characteristics, a statistical probability is computed for each class to determine the membership of each cell to a class within the signature file. An equal *a priori* probability weighting option is specified, allowing all classes to have the same *a priori* probability; resulting in each cell being assigned to the class to which it has the highest probability of being a member (Strahler, 1980).

Hydrologic Model

The hydrologic model used in this study is the Variable Infiltration Capacity (VIC) model (Cherkauer, Bowling, & Lettenmaier, 2003; Liang, Lettenmaier, & Wood, 1996; Liang, Lettenmaier, Wood, & Burges, 1994; Nijssen, Lettenmaier, Liang, Wetzel, & Wood, 1997). Since its inception nearly 20 years ago, VIC has undergone a variety of updates and has been extensively used in topics focused primarily on water resource applications ranging from climate change to land use change studies (Gao et al., 2010). Specifically, VIC has been applied to a number of large river basins over the continental United States and in different parts of the world (Abdulla, Lettenmaier, Wood, & Smith, 1996; Bowling, Storck, & Lettenmaier, 2000; Lohmann, Raschke, Nijssen, & Lettenmaier, 1998; Nijssen et al., 1997; Nijssen, O'Donnell, Lettenmaier, Lohmann, & Wood, 2001; Shi, Wood, & Lettenmaier, 2008; Su, Adam, Bowling, & Lettenmaier, 2005; Su, Adam, Trenberth, & Lettenmaier, 2006; Wood, Lettenmaier, Liang, Nijssen, & Wetzel, 1997; Zhu & Lettenmaier, 2007). To date, the VIC model has been cited over 1700 times from locations all around the globe, which proves the increased popularity of the model, the vast applicability and the widespread adoption it has received within the academic community. VIC's key characteristics that enable it to be practical for modeling purposes include the representation of multiple soil layers (min of 3) with variable infiltration, vegetative heterogeneity, and non-linear base flow (Gao et al., 2010).

VIC is a macro-scale, physically based, semi-distributed, land surface hydrologic model. The model operates by using 1/8° spatial resolution using gridded meteorological forcing data (precipitation, max/min temperature, and wind speed) in conjunction with

other watershed characteristic data (land cover, soil, elevation bands, snow bands, etc.) in order to estimate surface water runoff and base flow (Acharya, Piechota, Stephen, & Tootle, 2011; Acharya, Piechota, & Tootle, 2011). VIC functions based on the inputs and options selected within the ‘global parameter file’; this file is the main center for conveying information (names, locations, and formats for input and output files) to the VIC model so that simulations can be completed and results produced. For each individual grid cell in the model, simulations are executed and a time series of variables are output (runoff, base flow, canopy interception, soil moisture, evapotranspiration (ET), snow water equivalent, albedo, etc.) and stored separately in referenced flux files corresponding to the grid cell being modeled.

All simulations are performed at either daily or sub-daily time intervals based on whichever mode of operation has been selected in VIC, which is either in water balance or surface energy balance mode. It is important to understand that the water balance mode does not solve the energy balance, however, the energy balance mode will solve the total water balance; the energy balance mode not only solves the total water balance but also searches to minimize the surface energy balance error as well (Gao et al., 2010). When VIC is ran in the water balance mode only, it considers equal temperature between the soil surface and air for the current time interval, while the energy balance mode, simulates surface energy fluxes in order to compensate for incoming overall radiation fluxes (Acharya, Piechota, Stephen, et al., 2011). Compared to running VIC in the full water balance mode, which requires significantly less computational time, the energy balance mode requires more computational time and additionally requires sub-daily time

intervals as inputs. By running VIC in the energy balance mode, it allows for surface energy fluxes to be modeled, which are vital in understanding the hydrologic processes and land surface-atmosphere interactions within the basin (Gao et al., 2010).

In order to simulate streamflow, the results from VIC flux files must be post-processed with the use of a separate routing model (Lohmann, Nolte-Holube, & Raschke, 1996). The routing model operates by representing each grid cell as a node in a channel network. The routing model then sums the total surface runoff and base flow for each flux file for each individual grid cell and then produces a unit hydrograph that represents the distribution of travel times from the points of origin to the objective outlet point of the basin, which for this analysis is USGS streamflow gage 06630000.

For the routing model, there are a number of guidelines that are followed in order for successful routing to occur: 1) assume that most horizontal flow within the grid cell reaches the channel network within the grid cell before crossing over border into adjacent grid cell, 2) flow can exit each grid cell in a total of 8 possible directions, but all flow must exit in same direction, 3) the flow from each cell is ultimately weighted by the fraction of the total grid cell that lies within the basin's boundary (in some cases grid cells are cut off due to watershed boundary limitations), 4) once water flows into the channel network, it cannot flow back out and therefore must be removed from the hydrologic system. Ultimately, each grid cell's input into the channel network is routed throughout the basin by the use of simple linearized St. Venant's transfer functions which ultimately produce modeled streamflow values at the outlet of the basin (Gao et al., 2010).

Some important limitations of the VIC model are that all grid cells are simulated independently of each other. This means that when a simulation is run for a watershed, such as the NPRB with 95 grid cells, each grid cell is processed separately rather than being processed simultaneously and then iterating over the total number of allotted grid cells. Another limitation of VIC is that the routing of streamflow has to be performed separately from the land surface model by using a separate routing model developed by Lohmann et al. (1996). In addition to this, according to Zhu and Lettenmaier (2007), another potential source of uncertainty in VIC is with the great under and over-estimation of peak flows in some years, especially for arid and semi-arid basins, such as the NPRB.

Data Description

NAIP Imagery Data

Scale appropriateness of evaluation imagery was an important consideration when choosing an imagery dataset. The resolution of imagery selected for assessing should be appropriate for the features to be reviewed (Liknes, Perry, & Meneguzzo, 2010). O'Neill et al. (1996) suggests a resolution of one-fifth to one-half the size of the features of interest. Woodcock and Strahler (1987) recommends an image resolution of one-half to three-fourths the size of target objects. Because of the density of forest cover and the irregular locations of affected trees within the NPRB, in order to identify forest cover that has been affected by beetle kill within a dense area of unaffected trees, a high resolution imagery dataset was needed. In addition to this, the approximately 4175 mi² extent of the NPRB adds another constraint and narrows the choice of datasets even further.

From a macro-scale basin level perspective, assessing forest loss not only requires high resolution imagery, but imagery with extensive spatial and temporal coverage, as well. Since high resolution remote sensing data for land cover classification, such as LiDAR, are not always readily available or cost effective, especially for this particular project, an alternative high resolution dataset was found with the use of the National Agricultural Imagery Program (NAIP). NAIP is well suited to serve all these needs and is regularly used for land cover classification (Bales et al., 2011; Davies et al., 2010; Green & Lopez, 2007; Liknes et al., 2010). NAIP provides one meter ground sample distance (GSD) ortho imagery rectified to a horizontal accuracy of within +/- 5 meters of reference digital ortho quarter quads (DOQQ's) from the National Digital Ortho Program (NDOP) with coverage spanning the vast majority of the United States. The imagery is collected in natural color during the agricultural growing season and contains no more than 10% cloud cover. Since NAIP imagery is collected on a state by state basis, as a consequence, imagery for one state may not be available for the same year as a neighboring state. This was the case for Colorado and Wyoming. Beginning in 2003, NAIP was acquired on a 5-year cycle, with imagery being collected for Colorado in 2005 and Wyoming in 2006. Since these years were both before the beetle infestation became widespread, any differences in classification that might have occurred before this time period were considered negligible. However, NAIP began a 3-year cycle in 2009; resulting in complete coverage of both Colorado and Wyoming, and thus the entire NPRB.

The NAIP imagery were obtained from the USDA Geospatial Data Gateway website. These imagery are made available as either compressed county mosaics or uncompressed 3.75 minute by 3.75 minute quarter quadrangles with a 300 meter buffer on all sides. For labeling purposes, the period spanning up to and before 2005/2006 for the NPRB can be considered the “pre-beetle kill” era, whereas the period spanning up to and after 2009 for the NPRB can be considered the “post-beetle kill” era. Referencing these two periods was not completely accurate since beetle kill did not truly manifest in the NPRB until roughly 2007/2008, but for the purposes of labeling (Figures 2a & 2b) it was adequate. The green portions of the NPRB represent living unaffected forests, whereas the red represent dead affected forests. It can be seen from the figures that the bark beetle epidemic has severely impacted the forested regions.

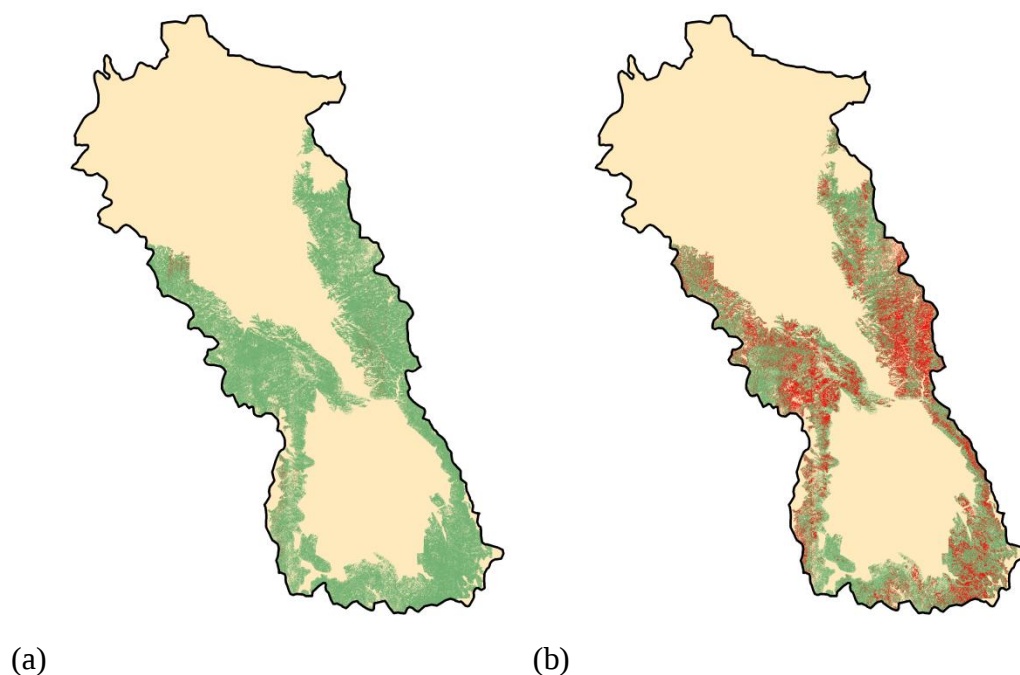


Figure 2. (a) Pre-beetle kill forest classification (2005/2006) using NAIP imagery.
(b) Post-beetle kill forest classification (2009) using NAIP imagery.

VIC Model Data

For this analysis, monthly observed historical streamflow data were collected from the USGS online database for the period 1950-2000. The particular streamflow gage of interest that was utilized for this study was USGS streamflow gage 06630000. By referring back to the location map (Figure 1), it can be seen that this gage is located in the most northern portion of the basin on the North Platte River just above Seminole Reservoir. This USGS gage, which is located in one of the lowest elevation areas within the NPRB, was utilized primarily because it allows for a better approximation for the total allotment of surface water runoff to congregate into streamflow and ultimately be observed.

In order to run successful model simulations, VIC requires a variety of meteorological forcing data from an array of credible sources. In order for VIC to complete a simulation, the model requires at a minimum precipitation (mm), max/min temperature ($^{\circ}\text{C}$), and wind speed (m/s). All input and output variables into the VIC model were in metric units and ultimately converted to English units for this analysis. In addition to the three previous forcing parameters mentioned, the following meteorological forcing data were also collected and implemented into VIC which includes vegetation, soil, and snow band data. All daily meteorological forcing data were acquired in order for results from VIC to be output and were obtained from the Soil and Water Modeling Group, University of Washington (www.hydro.washington.edu/SurfaceWaterGroup/data.php) (Maurer, Wood, Adam, Lettenmaier, & Nijssen, 2002). One of the most important pieces of data for this analysis was the land cover classifications as described by Hansen, DeFries, Townshend, and

Sohlberg (2000), which were based on and obtained from the Department of Geography, University of Maryland (<http://www.geog.umd.edu/landcover>). This data contains different land cover types all of which were at a one kilometer spatial resolution and consists of 14 total different land cover classes. For this analysis, the land cover in the NPRB did not consist of all 14 possible land cover classes that VIC specifies. Since this was the case, it was concluded that only 11 of the 14 land cover classifications were determined to apply for this analysis. Table 1 below reveals the 11 land cover classifications that were used to classify the entire vegetative coverage of the NPRB.

Table 1. VIC vegetation reference index.

# Class	Vegetation Classification
1	Evergreen Needleleaf
2	Evergreen Broadleaf
3	Deciduous Needleleaf
4	Deciduous Broadleaf
5	Mixed Cover
6	Woodland
7	Wooded Grasslands
8	Closed Shrublands
9	Open Shrublands
10	Grasslands
11	Crop Land (Corn)

The previously mentioned meteorological forcing data obtained from Maurer et al. (2002) were made available for $1/8^\circ$ grid cells for the conterminous United States. For this study, forcing data was downloaded from both the Colorado and Missouri River

basins since the NPRB lies partially within both domains. The meteorological forcing data used in this analysis were in a binary format and made available at daily time intervals for the period of 1950-2000. All of the gridded forcing data with spatial resolution of $1/8^\circ$ were based on USGS quadrangles, also known as ‘quads’, measuring exactly 7.5 minutes by 7.5 minutes. Because of the NPRBs location of the globe, each grid cell measures approximately 7.5 by 7.5 miles thus each complete grid cell measures roughly 56 mi².

In order for the VIC model to process all of the available data for each parameter file (soil, vegetation, and snow), they must all be referenced in the global parameter file to relay the geophysical information to VIC. The soil parameter file contains geographical information for each grid cell which includes soil parameters (initial layer moisture content, saturated hydrologic conductivity, thickness of soil moisture level, etc.). The vegetation parameter file defines different land cover types that are used during simulation, the number of vegetation types, and the fractional coverage (C_v) for each land cover type in each grid cell. Other vegetation parameters include (leaf area index, root depth, canopy resistance, etc.). In VIC, vegetation representation was based on a mosaic scheme where multiple vegetation types can be represented in a single grid cell. The snow band file contains information on each elevation band that was used by the snow model.

Model Simulations

VIC was initially developed to improve upon the representation of land surface processes within atmospheric models, but as of today, VIC has been extended to many

other uses such as simulating streamflow patterns over macro-scale basins for estimation purposes (Arnell, 1999). Additionally, the VIC model has been applied at a variety of scales ranging from global, to continental, to large watersheds (Mishra et al., 2010). For this analysis, all simulations were performed using the VIC model (version 4.1.1) downloaded from (<http://www.hydro.washington.edu/Lettenmaier/Models/VIC>) and were completed by using VIC's full energy and water balance mode of operation at daily time intervals with 1/8° spatial resolution. Because there have been previous modeling efforts using VIC within the NPRB, an existing calibrated model, developed by Dr. Anil Acharya, was used in this analysis. The VIC model that Dr. Acharya developed has been published in two literary journals (Acharya, Piechota, Stephen, et al., 2011; Acharya, Piechota, & Tootle, 2011). Specifically for the NPRB, VIC was initially calibrated and validated by Acharya, Piechota, Stephen, et al. (2011) by forcing historical meteorological forcing data into the model and then attempting to reproduce the historical trends in streamflow. According to Gao et al. (2010), the most common parameters for calibration include soil parameters such as infiltration, soil depth, base flow velocity, and soil moisture. In addition to calibrating soil parameters, Acharya, Piechota, Stephen, et al. (2011), concluded that six snow elevation bands would better represent snow processes for each of the grid cells in the NPRB as well. For this analysis, VIC was quite useful in the sense that it can be applied repeatedly over a large geographic domain (Arnell, 1999).

Similar to previous modeling efforts of Acharya, Piechota, Stephen, et al. (2011), the routing model was not used for this analysis due to the small basin size (only 95 grid cells) and the need to observe annual and decadal streamflow. VIC generates streamflow

for each individual grid cell, but in order to have an actual numerical value for the streamflow output from the model, the routing model of Lohmann et al. (1996) must be applied. In the case for this analysis, the routing model was not employed, so the total modeled streamflow for the entire NPRB was determined by the sum of each individual grid cells generated streamflow from each flux file, which would then represent the total streamflow at USGS gage 06630000. In order to calibrate VIC, Acharya, Piechota, Stephen, et al. (2011), used a univariate calibration method where the most sensitive soil parameters were selected and sensitivity analysis carried out to finalize each parameter. The sensitivity analysis for each parameter was based on model performance indicators. For hydrologic modeling, some commonly used indicators used to evaluate model performance in simulating streamflow include: Pearson Correlation Coefficient (r), Nash-Sutcliffe Efficiency (NSCE), Bias Percentage (Bias) , and Root Mean Square Error (RMSE) (Gao et al., 2010; Krause, Boyle, & Bäse, 2005; Wang et al., 2010). They are calculated as follows:

$$r = \frac{\sum_{i=1}^n (O_i - \bar{O})(M_i - \bar{M})}{(n-1)\sigma_O\sigma_M}$$

$$NSCE = 1 - \frac{\sum_{i=1}^n (O_i - M_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2}$$

$$Bias = \frac{\sum_{i=1}^n (M_i - O_i)}{\sum_{i=1}^n O_i} * 100\%$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (O_i - M_i)^2}{n}}$$

where O_i and M_i represent the observed and modeled streamflows respectively; σ_o and σ_m are sample standard deviations for the observed and modeled streamflows respectively; $\bar{O}$ and $\bar{M}$ are the average observed and modeled streamflows respectively; and n is the number of observations.

Scenario: Decrease Forest Cover to Emulate Beetle Kill

Aerial images for the NPRB were taken in 2005/2006 and again in 2009. For classification purposes, 2005/2006 was defined as the “pre-beetle kill” era or in other words, the endemic stage before the epidemic fully manifested itself. The 2009 image was defined as the “post-beetle kill” era or when the epidemic had progressed. In order to quantify the approximate amount of dead forests primarily due from beetle kill, NAIP aerial images from both 2005/2006 and 2009 were imported into ArcGIS and a maximum likelihood classification performed. ArcGIS outputs a classification raster for each aerial image and the difference in land cover change between the two periods showed that a 28% decrease in forested vegetation had occurred. ArcGIS then output a confidence raster based on the classification raster, which determined the approximate amount of uncertainty in this classification procedure. It was determined that an uncertainty of 12% was likely to occur in the classification procedures of the dead forests. From this classification analysis, a 95% confidence interval of 28% +/- 12% was established.

In order to mimic beetle kill for the affected areas throughout the NPRB, a variety of simulations that decreased forested land cover over the entire basin were implemented to show if changes in streamflow would become apparent. A total of five different runs

were performed with the VIC model to simulate decreases in land cover change due to beetle kill. Each individual run was decreased uniformly and not spatially over the entire basin, based on the results from the maximum likelihood classification. The following were the percent decreases in forested land cover change for each simulation ran in VIC respectively: 1) 16%, 2) 22%, 3) 28%, 4) 34%, and 5) 40%, which are based on a 95% confidence interval.

In order to simulate land cover change by the respective amounts above, the vegetation parameter file that contains each of the 95 grid cells being modeled in VIC along with each land cover classification for each grid cell had to be modified. Each individual grid cell within the VIC model contains a certain number of land cover types. Referring back to Table 1, for the NPRB there are a total of 11 classifications that can reside within each grid cell. As stated previously, the NPRB contains $95 \frac{1}{8}^{\circ}$ grid cells, but of those 95 cells, not all of them have been affected by beetle kill. Beetle kill only affects trees, thus forested land cover was the only land cover type being affected. By using aerial images in ArcGIS, it was concluded that of the 95 total grid cells in the NPRB, only 54 of those cells contained forest cover (Figure 3). For this analysis, “forest coverage” was defined as only land cover classes #1-6 (refer back to Table 1) in order to be consistent.

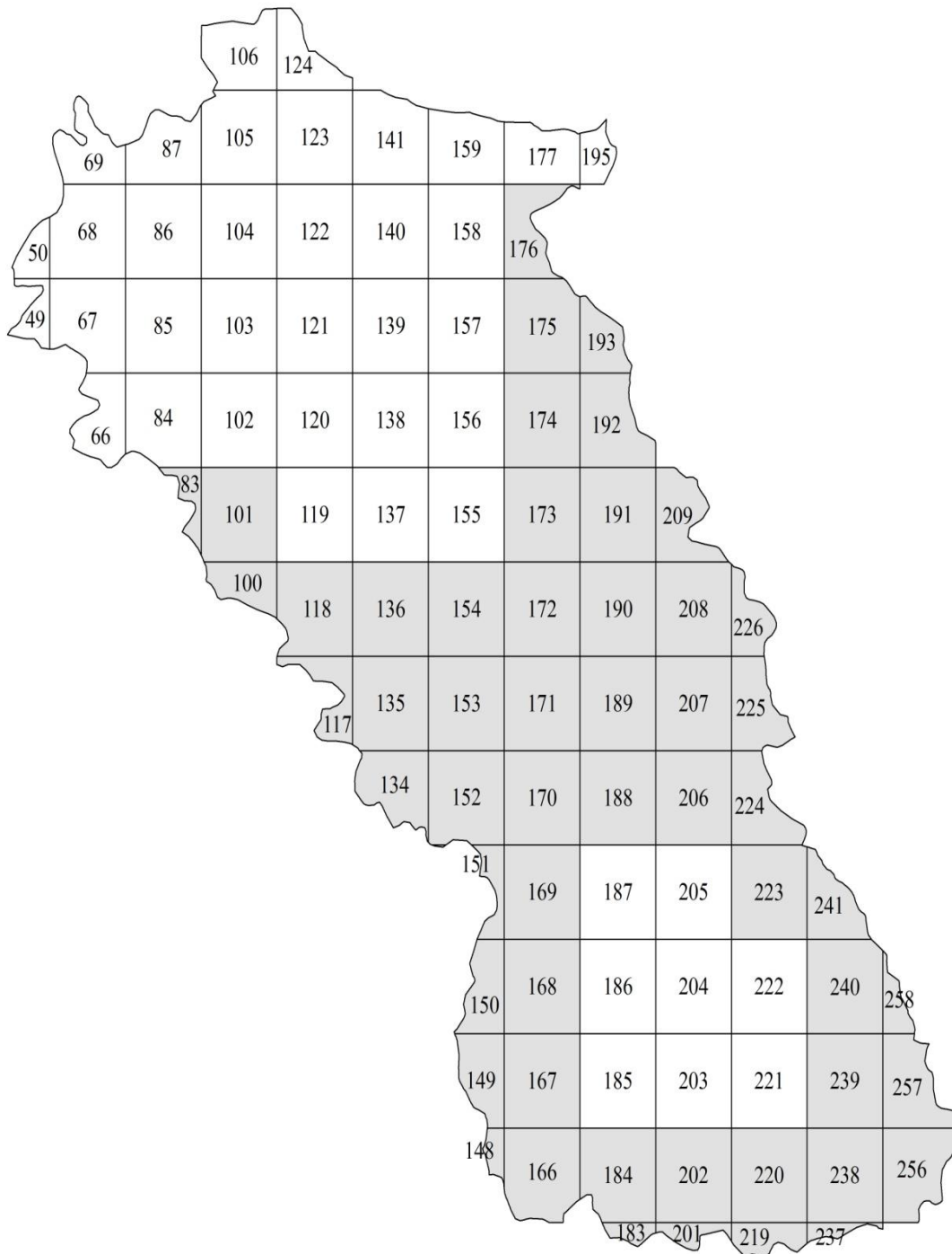


Figure 3. North Platte River Basin with all 95 grid cells shown and all 54 forested grid cells highlighted.

For each of the 54 forested grid cells, if a grid cell contained land cover classification #1-6, then the value of the fractional coverage (C_v) for that particular land cover type was decreased by the specified amount for whichever of the five simulations were currently being performed. If a grid cell contained multiple types of forested vegetation, which occurred in most of the grid cells, then the percent decrease was divided by the total number of forest cover type classes #1-6 and then evenly distributed amongst the total number of forested land cover types within the grid cell. Once this was completed, then the total percent decrease that was applied for that particular scenario was then added to a less influential hydraulic land cover class, which for this analysis was assumed to be grasslands. In order to try to rationalize what was occurring in the NPRB, if a forest was initially in place and then was affected by beetle kill, in the process of modeling in VIC, it was concluded that the forest would basically transition from forest to grassland. In order to simulate decreasing forest cover in VIC, because all the total fractional coverage's for each land cover type in a grid cell had to sum to one, the above mentioned procedure was carried out for each of the 54 forested grid cells. In essence, for modeling purposes, it was assumed that a forest affected by beetle kill would become somewhat more hydraulically similar to that of grassland, thus enabling a greater potential for surface water runoff to occur and potentially equivalating into increased streamflow. The above rationale was applied to each of the 5 previously mentioned simulations by use of VIC and modeled streamflow results produced.

Hypothesis & Uncertainty

By examining a simple water balance for the NPRB and having some knowledge of beetle kill and its effects, it can easily be conceived that the major component of the water budget affected would be the amount of transpiration (water absorption by trees) throughout the forested areas of the basin. Since massive amounts of trees have fallen victim to beetle kill over the entirety of the basin, the potential for an increase in streamflow appears possible because less precipitation would be absorbed by the tree's roots and canopy layer. Based on previous studies (Bethlahmy, 1974, 1975; Love, 1955; Potts, 1984) of beetle infestations in the western United States, there has been a general consensus that extensive tree mortality should noticeably increase water yield at the basin scale and lead to earlier peak runoffs (Lukas & Gordon, 2010). However, because there has not been any compelling evidence yet to show the link between streamflow changes caused by beetle infestation, this has given more reason to suggest that the story of changing land cover is much more complex than the simple formulation that fewer live trees will ultimately yield more runoff thus increased streamflow. For this analysis, the hypothesis assumes that a decrease in the amount of forested land cover due to beetle kill will produce an increase in the amount of modeled streamflow at USGS streamflow gage 0630000 located in the NPRB. The goal of this analysis is to observe the differences between historical observed and modeled decadal streamflow for the period 1950-2000 and determine if the current beetle epidemic would have had any effects on the streamflow for the NPRB in past decadal periods. By performing this analysis, it will

provide greater insight and understanding of the potential impacts on streamflow for the NPRB in the future.

However, there were a number of limitations for the current research approach employed that may have impacted the uncertainty of the results. According to Zhu and Lettenmaier (2007), the VIC model has been proven to not function as effectively in arid and semi-arid environments, as it has in other climatic regions. In many cases, when VIC is utilized in a semi-arid environment, like the NPRB, modeled streamflow can be either under or over-estimated for peak flows. Additionally, VIC was simulated in the full energy balance mode, similar to previous research efforts by Acharya, Piechota, Stephen, et al. (2011), and the routing model was not used.

While uncertainty exists in nearly every dataset, it was concluded that for this analysis that the NAIP dataset was the most appropriate because of the high spatial resolution, cost effectiveness, and the ability to cover very large areas. Even with this understanding, uncertainty still exists in the NAIP dataset, where results revealed a 28% loss of canopy coverage with error estimated at $\pm 12\%$. In accordance with the five VIC model runs, each loss of canopy coverage was applied homogeneously throughout all 54 cells identified as having tree cover. This procedure of homogeneously decreasing canopy coverage is understood to be impractical because in the real-world, canopy loss will likely vary heterogeneously and not uniformly throughout the basin. Further uncertainty was also presented when canopy coverage was decreased uniformly throughout forested cells then equally distributing the percent loss over the six forested classifications; the total percent loss was then added back into the grid cell, but under the

land cover classification of grassland. However, this equal distribution will likely vary based on the distribution of tree species within each cell. Tree mortality is highly variable and is based on numerous biotic and abiotic factors including species type.

The current macro-scale analysis assumes that all trees affected by beetle kill are “immediately” dead with the new classification being grasslands. According to Pugh and Gordon (2012), when bigger trees die, this allows for the understory of the forest to regenerate quickly, thus yet another cause of uncertainty. Modeling efforts may not reflect the transpiration rates of new tree growth from regeneration. Therefore, field transpiration rates are likely higher than reflected in the current model scenarios. With this being the case, the modeled streamflow for these scenarios will likely be greater than actual conditions. While it is likely transpiration will decrease slightly, a combination of both evaporation and melting of snowpack will likely increase due to canopy loss and the increased impacts of solar radiation, albedo, and wind on the snowpack. Thus, another source of possible over-estimation of modeled streamflow for the land cover change scenarios.

Chapter 3

Results and Discussion

Land Cover Classification Results

In all, there were two classifications, one before the beetle infestation became widespread, or pre-beetle kill, and one for after the beetles had affected the basin, or post-beetle kill (refer back to Figure 2). Pre-beetle kill classification was done using NAIP imagery from 2005 for Colorado and 2006 for Wyoming, with the reasoning for the differing years being due to the aerial images being flown at different times on a state by state basis. Post-beetle kill classification was done using NAIP imagery from 2009 for both Colorado and Wyoming. The pre-beetle kill classification was used as a baseline from which to measure the decrease in forest cover in the post-beetle kill classification. The resultant forest cover decrease was then used to modify the land cover parameters in the VIC model.

Along with each output classification raster, the mean vector and the variance-covariance matrix were used to create an output confidence raster from which confidence intervals were constructed for each classification. Knowing the mean and confidence intervals, a population density function was created and subsequently used to vary the forest cover decrease in the VIC model, capturing the uncertainty in the classification results.

The pre-beetle kill classification resulted in approximately 2% of the total existing forested land being classified as dead. The percent of dead forest cover increased to a total of approximately 30% with the classification of the post-beetle kill

imagery, thus a 28% decrease in forested land cover from 2005/2006 to 2009, with an uncertainty of $\pm 12\%$. Since this maximum likelihood classification analysis was based on a normal distribution, the 28% decrease in forested cover was considered to be the mean with the uncertainty of $\pm 12\%$ representing two standard deviations away from the mean. Ultimately, a 95% confidence interval was established, 28% $\pm 12\%$, which serves as the basin level estimate of the forest loss with associated uncertainty.

VIC Results

Model Calibration and Validation

The model was calibrated and validated with respect to the historical monthly observed streamflow, for the period of 1950-1980 and 1981-2000, respectively (Figures 4a & 5a). The monthly data for USGS streamflow gage 06630000, which is located at the most downstream point of the watershed and just upstream from the Seminole Reservoir, was used for this purpose. For the calibration period, an r (0.86), NSCE (0.66), Bias (1.67%), and RMSE (5.34×10^{-2} million acre-feet, MAF) were obtained, with predominately over-estimation of the peaks being observed. For the validation period, an r (0.84), NSCE (0.61), Bias (-0.11%), and RMSE (6.08×10^{-2} million acre-feet, MAF) were obtained, with a combination of both under and over-estimation of peaks being observed. A positive bias simply means that the modeled streamflows were higher than the observed streamflows and vice versa for negative bias. One of the primary purposes for matching the observed and modeled streamflows together through calibration ensures that ET was modeled realistically over the entire basin and for a sufficiently long enough time (Gao et al., 2010). Based on Zhu and Lettenmaier (2007) observations of calibrating

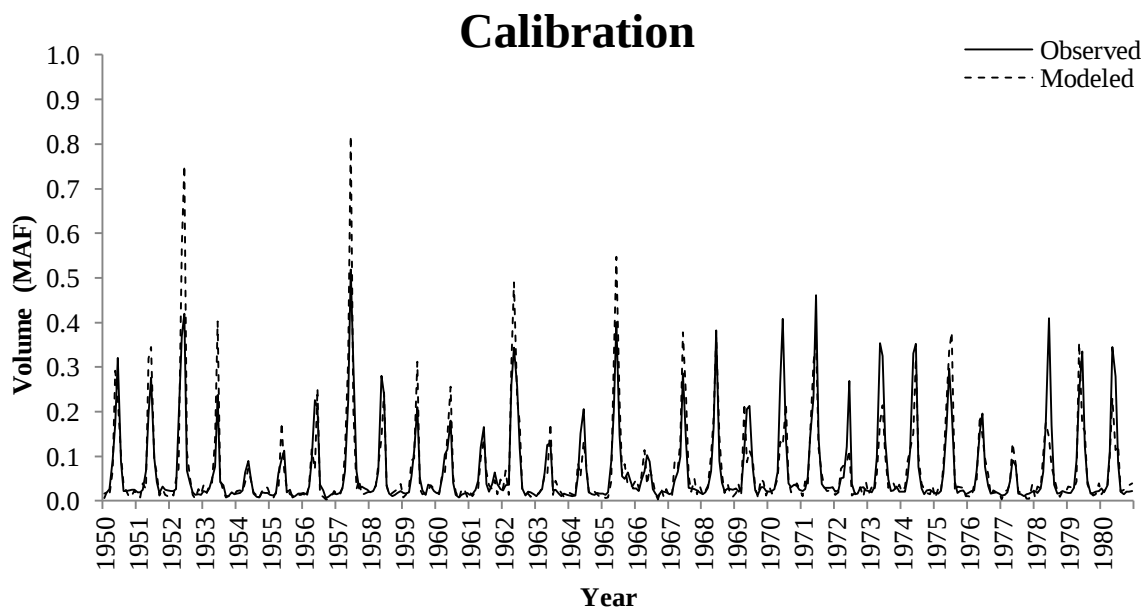
watersheds throughout Mexico, it was discovered that VIC did a good job of capturing the peak time and temporal pattern of streamflow for both arid and wet regions, however, the one problem that seemed to manifest was the great under or over-estimation of peak flow in some years especially for arid and semi-arid environments; this was the case for the NPRB which can be seen in Figures 4a and 5a.

In order to properly calibrate VIC, the normal approach involves the calibration of six soil parameters; they are as follows: 1) the infiltration parameter (b_{inf}) which controls the amount of precipitation that will infiltrate and runoff directly (higher values of b_{inf} give lower infiltration and yield higher surface runoff), 2) the second and third soil layer thicknesses (D_2 and D_3 ; with D_1 being the top soil layer), 3) the base flow parameters of Ds_{max} , D_s , and W_s which stand for the maximum base flow velocity, fraction of maximum base flow velocity, and fraction of maximum soil moisture content of the third soil layer (D_3), which is where non-linear base flow occurs, respectively (Nijssen et al., 1997). All three of the base flow parameters determine how quickly the water stored in the third soil layer will be evacuated as base flow (Liang et al., 1994). For calibration purposes, all three base flow parameters (Ds_{max} , D_s , and W_s) and the third soil layer depth (D_3) were used for only fine tuning the final calibration; the infiltration parameter (b_{inf}) and second soil layer depth (D_2) were the primary drivers for final calibration and both variables were calibrated independently of one another (Nijssen et al., 2001; Su et al., 2005).

Given the calibrated model for the entire NPRB, developed by Dr. Anil Acharya, which has currently been published in two academic journals (Acharya, Piechota, Stephen, et al., 2011; Acharya, Piechota, & Tootle, 2011), it was utilized for the

streamflow analysis. The scatter plots in Figures 4b and 5b show a good correlation between the modeled and observed streamflows at lower magnitudes, while there is some minimal scattering at higher magnitudes. According to Acharya, Piechota, Stephen, et al. (2011), the final calibrated parameters for VIC were: infiltration parameter ($b_{inf} = 0.19$); maximum base flow ($Ds_{max} = 11$ mm/day); fraction of Ds_{max} ($D_s = 0.04$); fraction of maximum soil moisture ($W_s = 0.15$ mm/day); and second soil layer depth ($D_2 = 0.30$ m).

(a)



(b)

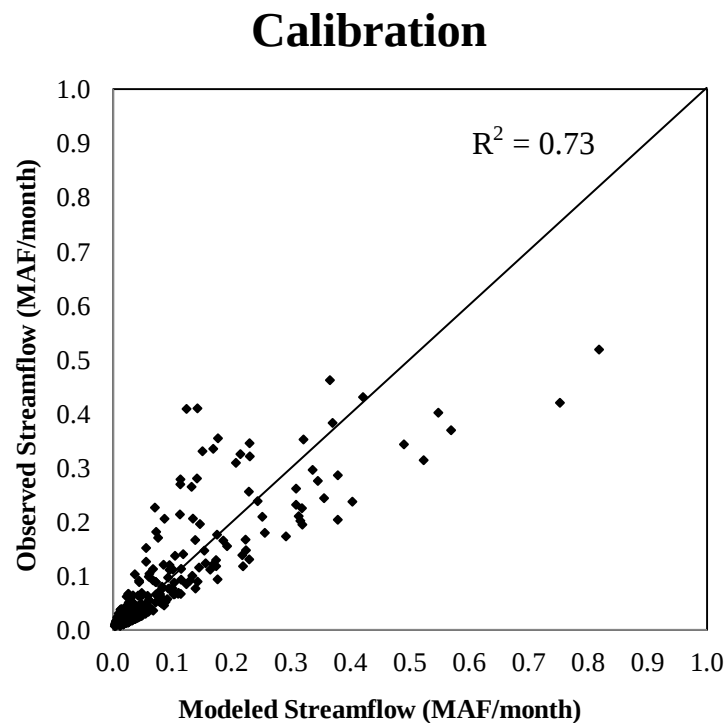
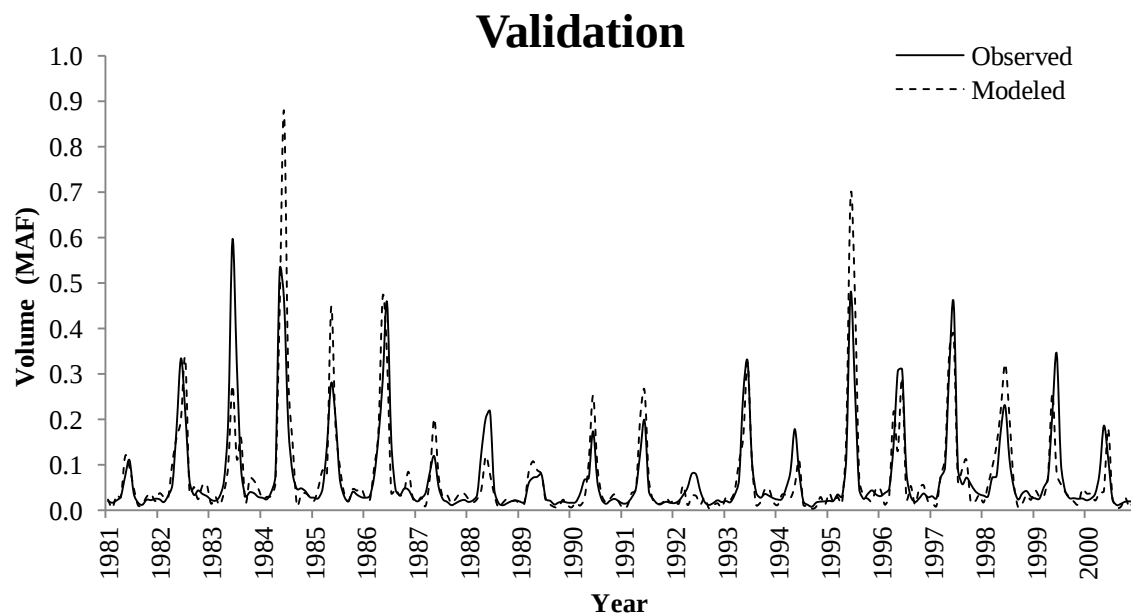


Figure 4. (a) VIC model calibration based on observed monthly streamflow (million acre-ft, MAF) during 1950-1980. (b) Scatter plot of observed vs. modeled monthly streamflow during the calibration period.

(a)



(b)

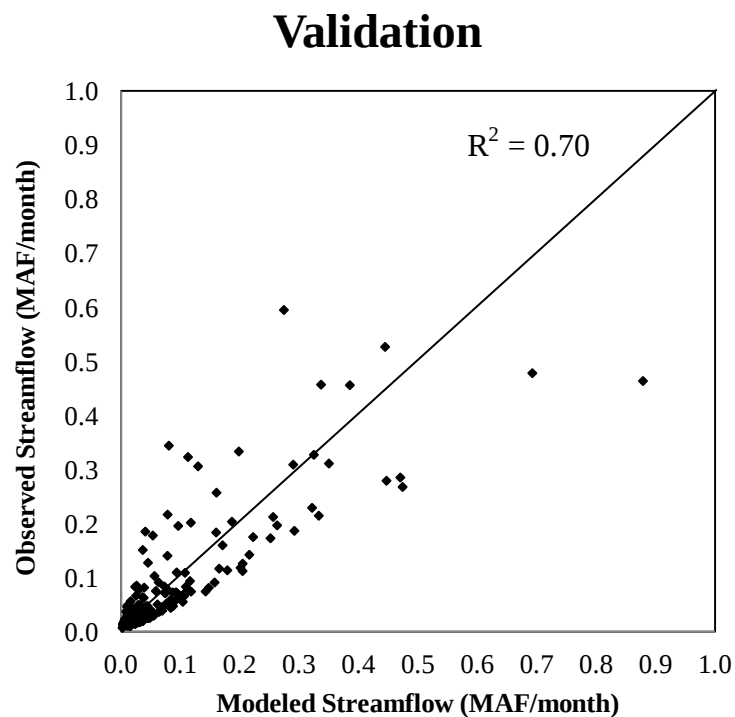


Figure 5. (a) VIC model validation based on observed monthly streamflow (million acre-ft, MAF) during 1981-2000. (b) Scatter plot of observed vs. modeled monthly streamflow during the validation period.

Scenario: Streamflow Response Due to Land Cover Change

By decreasing tree cover loss in the designated 54 forested grid cells in VIC by the specific amounts (16%, 22%, 28%, 34% and 40%) based on the results from the maximum likelihood classification performed in ArcGIS, cumulative annual modeled streamflow results were obtained for the period of 1950-2000. In order to capture uncertainty in this analysis, impacts of streamflow due to beetle kill were observed by looking at each of the five decadal periods (1950-1959, 1960-1969, 1970-1979, 1980-1989, 1990-2000). In order to compare the results obtained from VIC, annual streamflows were summed together for each of the corresponding decades to return a single cumulative value for each decade's streamflow volume in units of million acre-ft (MAF). Uncertainty was captured by varying the forested vegetative cover from 16% to 40%, which was based on a Gaussian distribution. Additionally, uncertainty was also captured by looking at each of the corresponding five decadal periods, given that some were wetter/dryer than others, to see how this streamflow was impacted by beetle kill. By looking at the results from each respective decadal period, it displayed how streamflow would have changed had beetle killed manifested itself in the past as it has presently. By understanding the effects from the beetle kill infestation in the past, an estimate could be made as to how the effects of beetle kill could present itself in the near future.

The results for the decrease in land cover based on the maximum likelihood classification, 28% +/- 12%, that was performed in ArcGIS were based on a Gaussian distribution. Since the decrease in land cover change was based on a Gaussian distribution, then 28% can be considered to be the mean, with 22% and 34% being within one standard deviation of the mean and 16% and 40% being within two standard

deviations of the mean. In order to present a truer value for the amount of streamflow being modeled due to beetle kill, it was proposed that a weighted average of the five model simulations for the decrease in land cover be implemented. By doing this, it allowed streamflows from decreases in land cover of 28% to be weighted more (68.2%) than the decreases in land cover of 16% and 40% which had a probability of (2.3%).

The weighting of the different modeled streamflow simulations, that were based on the amount of land cover loss, were performed in association with the empirical rule (68-95-99.7) of statistics, which states that for data following a Gaussian distribution, nearly all values lie within three standard deviations of the mean. Applying this rationale to the 95% confidence interval, 28% $\pm$ 12%, from the maximum likelihood classification, 28% is considered to be the mean with 22% and 34% being within $\pm$ 1 standard deviation of the mean and 16% and 40% being within $\pm$ 2 standard deviations of the mean. According to the empirical rule of statistics, about 68.2% of the values being evaluated lie within $\pm$ 1 standard deviation of the mean. Additionally, about 13.6% of the values being evaluated lie within $\pm$ 2 and $\pm$ 1 standard deviations of the mean respectively for a total of 27.2%. Lastly, about 2.3% of the values being evaluated lie greater than $\pm$ 2 and equal to $\pm$ 2 standard deviations of the mean respectively for a total of 4.6%. Figure 6 shows the exact percentages that each of the five simulations were multiplied by in order to obtain a “model-weighted” value for each of the five decadal periods. All of the modeled streamflows were weighted by the certain percentage that corresponded to their position on the Gaussian distribution plot. This modeled-weighted streamflow was incorporated into this analysis to ensure that more weight was given to

the modeled streamflow volumes that were more centered around the mean amount of forested land cover loss actually predicted of 28%.

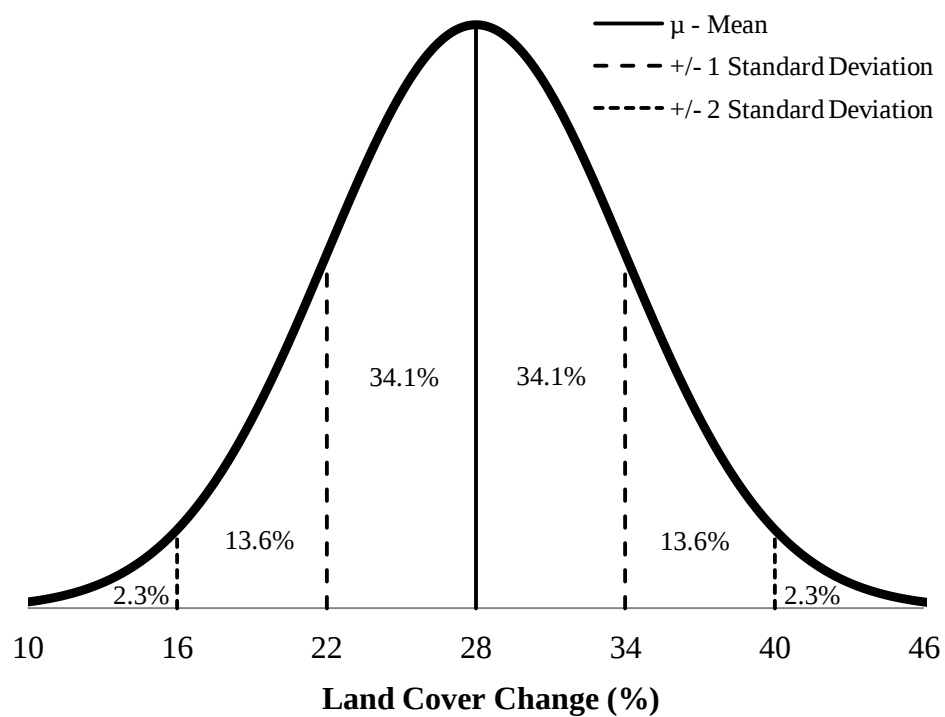


Figure 6. Land cover classification with 95% confidence interval (28% $\pm$ 12%) based on a Gaussian distribution.

For this analysis, error bars were constructed based on the 95% confidence interval, 28% $\pm$ 12%, of forest cover loss with uncertainty. Each of the lower and upper bounds of the error bars represent the 2.5th and the 97.5th percentiles respectively which have been based on a two-tailed Gaussian distribution and in association with the 68, 95, 99.7 rule of statistics. For the period of 1950-2000, Figure 7 shows the observed, modeled (no beetle kill), and model-weighted (with beetle kill) streamflow volumes in MAF for each respective year with 95% confidence level error bars displayed.

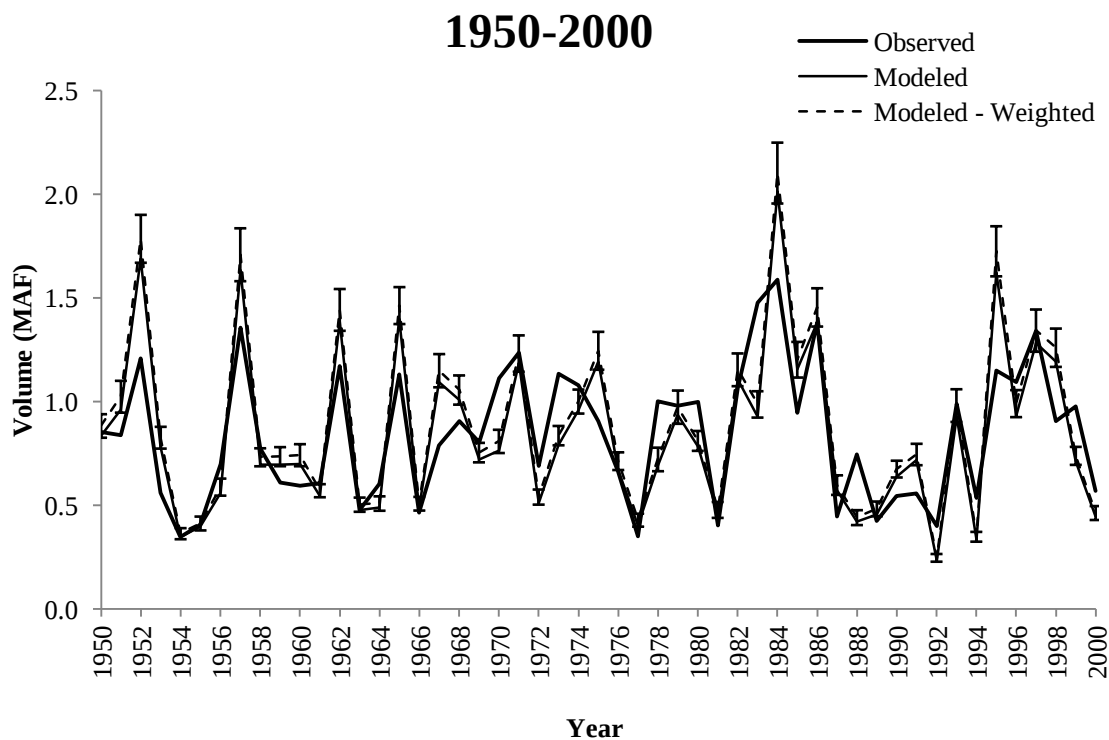
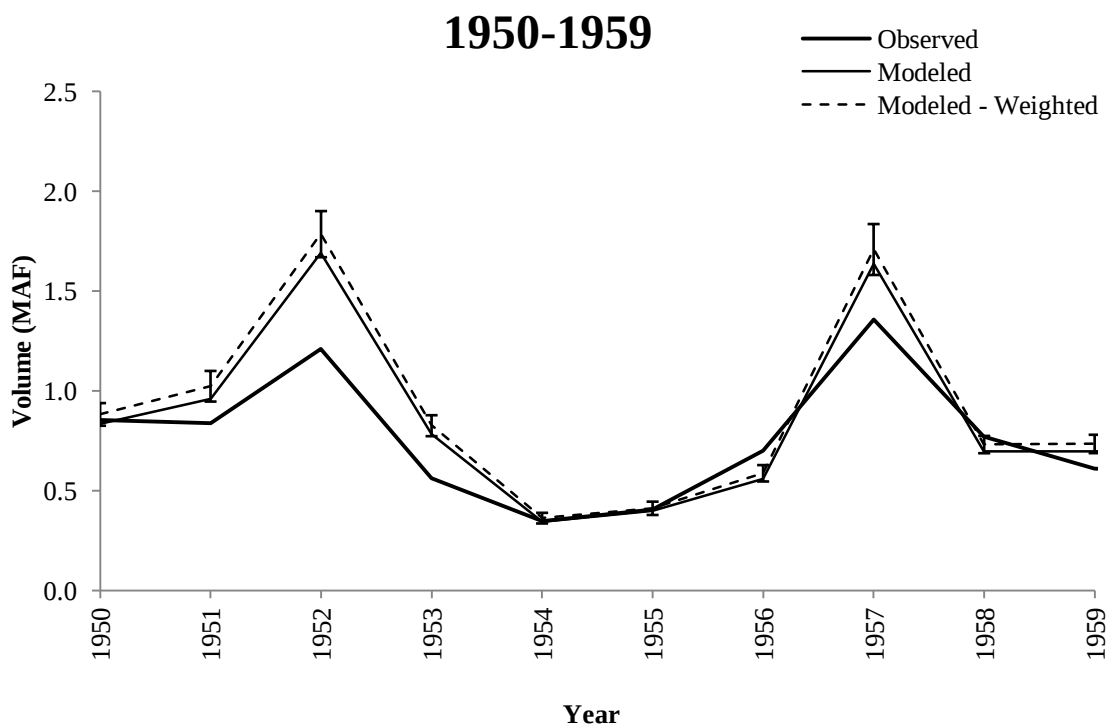


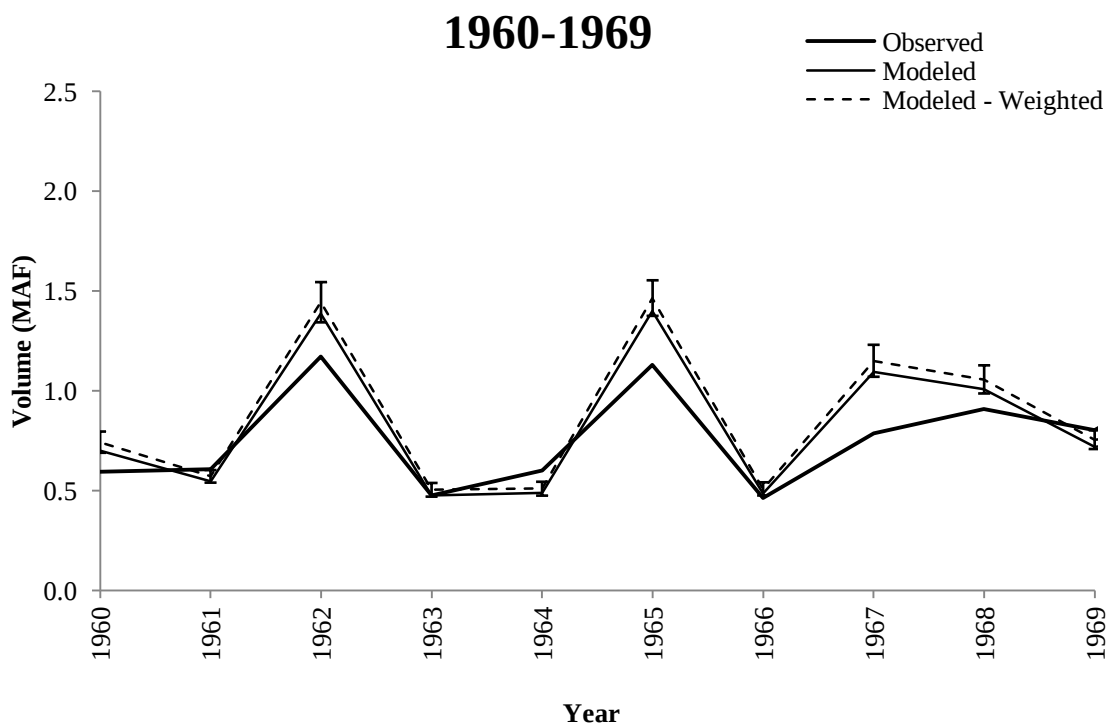
Figure 7. Cumulative yearly streamflow volumes (MAF) for the period of 1950-2000 showing 95% confidence interval error bars.

In order to determine if beetle kill had a significant impact on streamflow in the NPRB, the following decadal plots were constructed:

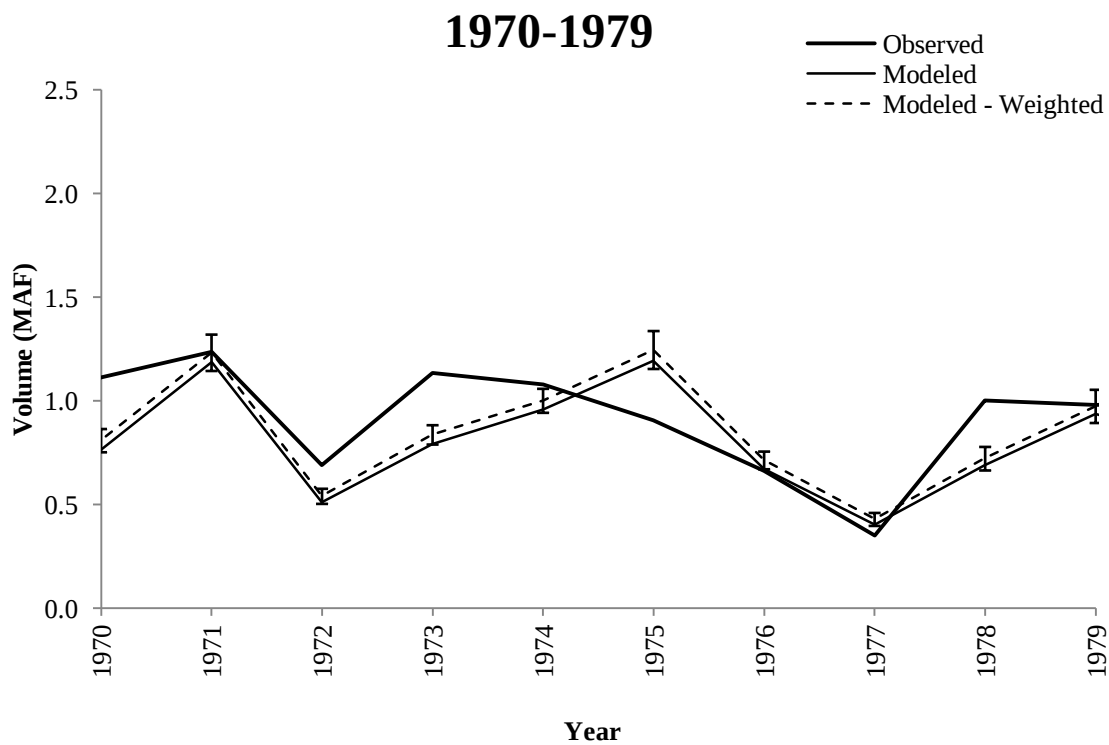
(a)



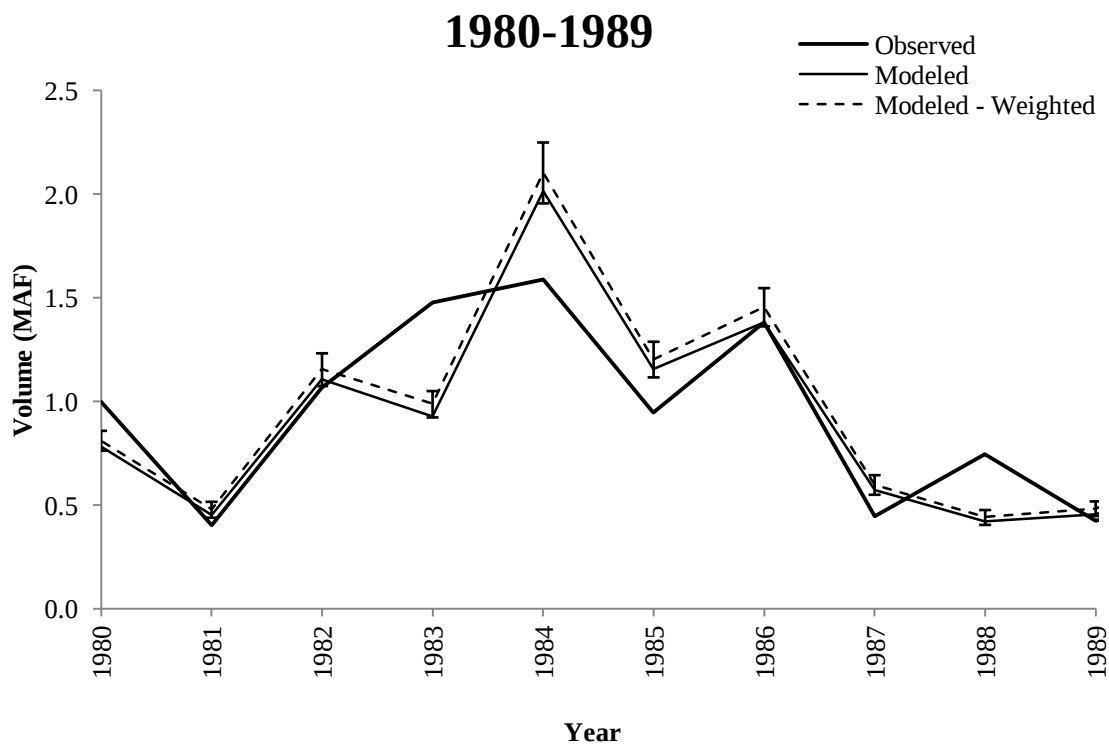
(b)



(c)



(d)



(e)

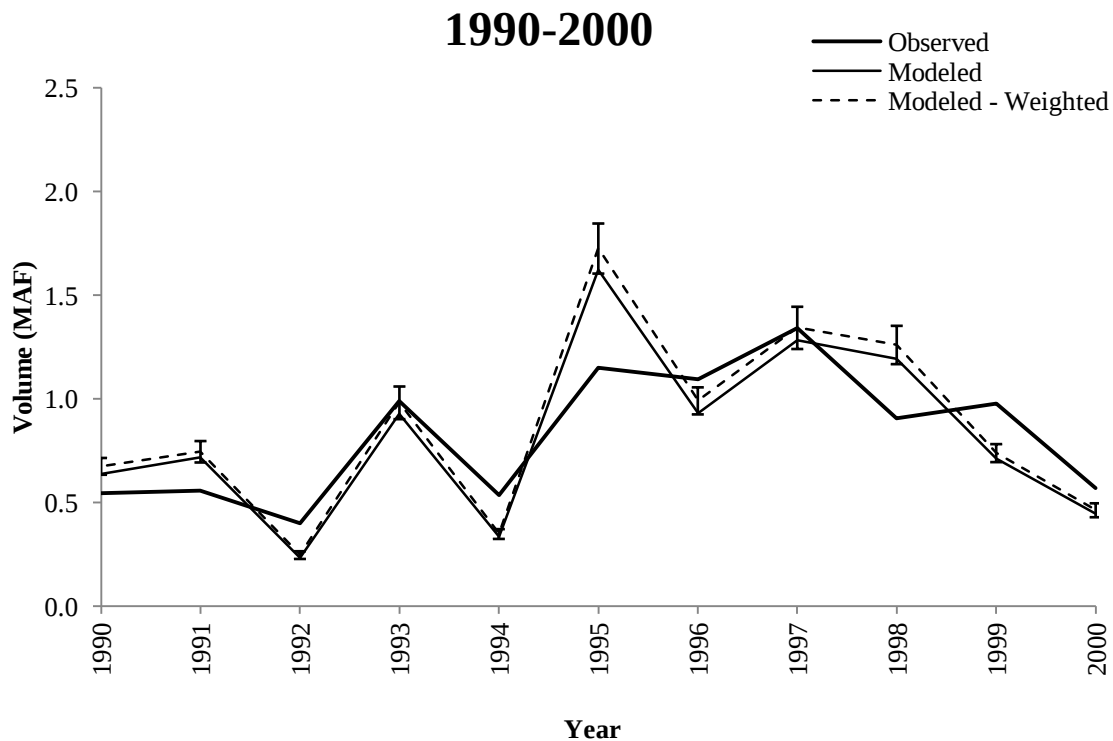


Figure 8. (a)-(e) Cumulative yearly streamflow volumes (MAF) for each respective decade with error bars showing a 95% level of confidence for forest loss cover of (28% +/- 12%).

In each of the five decadal plots of streamflow volume, observed, modeled (no beetle kill), and modeled –weighted (with beetle kill), where 95% confidence level error bars, were shown (Figures 8a-e). As displayed, nearly all of the modeled (no beetle kill) streamflow volumes lay within the 95% confidence domain of the error bars. Based on this analysis, it can be seen that the modeled –weighted (with beetle kill) did not vary much from the modeled (no beetle kill), suggesting that decreasing land cover change due to beetle kill did not cause significant increases in streamflow.

The impacts of beetle kill on streamflow have been summarized in Table 2. The data presented here shows annual streamflow that have been cumulatively summed together for each respective decade for observed, modeled and modeled weighted. In addition to this, the decadal streamflow was produced for each change in land cover simulation within VIC. It can be seen that for each of the five simulations, that has land cover continually decreased, streamflow steadily continues to increase. Another point that should be mentioned is that the modeled weighted averages were approximately equal to the average land cover loss of 28%. This suggests that there was little variability for the streamflow response to the different changes in land cover.

Table 2. Cumulative yearly streamflow volumes (MAF) for each specific decade showing the Observed, Modeled, Modeled-Weighted and each of the 5 land cover change simulations modeled in VIC.

Period	Forest Loss							
	Volume (MAF)							
	Observed	Modeled	Modeled Weighted	-2 σ (16%)	-1 σ (22%)	μ (28%)	+1 σ (34%)	+2 σ (40%)
1950-1959	7.65	8.60	9.07	8.72	8.89	9.05	9.34	9.44
1960-1969	7.54	8.30	8.71	8.41	8.53	8.70	8.91	9.11
1970-1979	9.15	8.10	8.51	8.21	8.31	8.50	8.72	8.91
1980-1989	9.47	9.27	9.72	9.39	9.58	9.69	9.98	10.21
1990-2000	9.06	9.03	9.53	9.14	9.32	9.52	9.75	9.96

Table 3 looks at the percent increase in decadal modeled streamflow as compared to the original modeled streamflow. Modeling efforts suggest that an increase in decadal modeled streamflow of approximately 1% to 10% for a decrease in land cover ranging from 16% to 40% will occur. However, the average change in decadal streamflow volume for the NPRB can be expected to be somewhere in the realm of a 5% increase for the average decrease in land cover of 28%. A 5% increase in decadal streamflow volume would yield a 0.40 to 0.50 MAF increase in decadal streamflow volume for the NPRB (Table 4).

Table 3. Percent increase in decadal streamflow for each of the 5 land cover change simulations.

Period	Change in Decadal Streamflow (%)				
	16%	22%	28%	34%	40%
1950-1959	1.37	3.34	5.19	8.62	9.81
1960-1969	1.24	2.74	4.74	7.26	9.68
1970-1979	1.38	2.60	4.91	7.57	10.02
1980-1989	1.32	3.34	4.48	7.63	10.13
1990-2000	1.23	3.24	5.48	7.97	10.31

Table 4. Numerical increase in decadal streamflow volume (MAF) for each of the 5 land cover change simulations.

Period	Streamflow Volume Increase (MAF)				
	16%	22%	28%	34%	40%
1950-1959	0.10	0.26	0.40	0.66	0.75
1960-1969	0.09	0.21	0.36	0.55	0.73
1970-1979	0.13	0.24	0.45	0.69	0.92
1980-1989	0.12	0.32	0.42	0.72	0.96
1990-2000	0.11	0.29	0.50	0.72	0.93

The following are possible sources of uncertainty in this analysis on streamflow due to beetle kill: 1) VIC has been historically known to not perform as well in arid and semi-arid environments, such as the NPRB, because the model has problems with under or over-estimating peak flows for some years. By referring to back to Figure 4a, it is visually seen that VIC has slightly over-estimated the modeled streamflow; additionally, the calibration period (1950-1980) produced a positive bias confirming that modeled streamflow was favored over the observed. 2) The NAIP aerial imagery data did initially present itself with uncertainty, but it was realized every dataset has some degree of associated uncertainty. However, because the NAIP imagery was thought to be the best available dataset for a variety of reasons, it was employed. 3) For each simulation, forest cover loss was uniformly decreased across all forested grid cells, but in reality land cover should have varied spatially to limit uncertainty. 4) It was decided that for modeling purposes, if a tree was “dead” then it would hypothetically act the same way hydraulically as grassland, which was an assumption and has potential associated uncertainty. 5) For this analysis, when forested vegetative cover was decreased, it was assumed to be either “alive” or “dead”. According to Pugh and Gordon (2012), this is a common misconception because a tree cannot be considered “alive” one second and then once infected by beetle kill, “dead” the next second. The death of a tree due to beetle kill is a gradual process that can take up to a year and a half depending on the tree species. 6) Lastly, when interpreting aggregated data such as this, it is important to be aware of the Modifiable Areal Unit Problem (MAUP) and its effect; depending on how the data is aggregated, be that different sized and/or positioning of the grid cells, the results may

change to some degree. The MAUP is a potential source of bias that can affect spatial study results, which utilize aggregate data sources (Unwin, 1996).

According to Pugh and Gordon (2012), there are 6 stages for the life of a tree when associated with beetle kill. Initially, all healthy trees, prior to beetle infestation are considered in Stage 0: undisturbed forest, where natural hydrologic processes are functioning properly. Once beetle kill has commenced within the tree, the tree has entered into Stage 1: green phase, where the tree begins to slowly die due to lack of nutrients. At this stage, the tree retains its green needles but quickly begins reducing ET rates due to lack of absorption from the root system. This ultimately increases the amount of moisture remaining in the soil. Within about a year, the tree will enter into Stage 2: red phase, where all the needles have turned red and then eventually brown. At this point ET and other natural processes within the tree have ceased entirely and the tree can be considered completely dead.

Based on Pugh and Gordon (2012) discussion of the phases that trees go through, this could potentially be a source of uncertainty for this analysis since we do not know how many trees are in what stage of beetle kill. Obviously, the trees, most of which are lodgepole pine, that were affected initially when beetle kill occurred in the NPRB around 2007/2008 are probably entering into Stage 3: grey phase in which they are essentially skeletons with only trunks and branches exposed. However, trees that have been recently, within the last year or two, affected could possibly still have some functioning ecohydrologic processes within them, thus the reason for our uncertainty. It is also important to realize that as the trees enter Stage 4: tree fall phase, where trees have died

and begun falling to the ground, this can have a tremendous impact on the saplings and other smaller trees located in the understory of the forest. As the bigger trees die, many of the smaller trees in the understory will become more susceptible to more amounts of precipitation, due to the fact that the larger tree canopies are completely gone, and will commence the process of absorbing more water from the ground. This process that has just been described is the beginning steps of Stage 5: forest regeneration.

Chapter 4

Conclusions and Recommendations

Conclusions

This paper developed a hydrological (VIC) model which evaluated the impacts of beetle kill on streamflow within the NPRB. The impacts of the current (2009) land use change due to beetle kill infestation have been applied to past (1950-2000) decadal periods using historical meteorological forcing data to attempt to model beetle kill in the past and determine the results on streamflow. By performing this analysis, the potential effects of beetle kill on past streamflow could be applied to the present day conditions and possibly predict future water yields.

Based on this analysis, it was concluded that the potential effects of beetle kill would increase decadal streamflow by approximately 1% to 10% for a decrease in forested land cover of 16% to 40%. For this analysis, it is believed that the average of 5% increase in streamflow is an over-estimation due to modeling limitations and assumptions. It is well recognized that the VIC model has limitations within semi-arid environments. In this analysis, it was assumed that a tree was either “alive” or “dead”, which could cause results to be misrepresented. Because of Pugh and Gordon (2012) analysis, the death of a tree is not immediate, thus in addition to the understory taking in water, the dying trees could be taking in small amounts of water as well. Additionally, the loss of canopy cover will likely increase evaporation, due to increased solar radiation and wind impacts, of the snowpack. For this reason, it is felt that the 5% increase in streamflow due to beetle kill is more than likely an over-estimation.

Further research will be performed by using the same calibrated model in the NPRB to model how beetle kill has affected ET. The VIC model does not allow ET to be input, but it does create model output. Thus, a future goal is to compare modeled ET from VIC with in situ ET values from the NPRB.

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Vita

Jordan Rudolph was born in Memphis, TN on February 20, 1989. He grew up in the small suburb of Cordova, on the outskirts of Memphis, TN where he attended Cordova High School and graduated in 2007. Beginning in the Fall of 2007, he attended Christian Brothers University (CBU), a small Christian college in Memphis, where he pursued a degree in engineering and played basketball as a walk-on. At the end of the Spring 2008 semester, he decided to transfer from CBU to the University of Tennessee Knoxville (UTK). He spent the next three and a half years obtaining an undergraduate degree in the field of civil engineering in which he graduated Summa Cum Laude. Presently, Jordan is in graduate school at UTK and currently working on his master's thesis titled "Impacts of Beetle Kill on Modeled Streamflow Response in the North Platte River Basin". Jordan currently has a Bachelor of Science degree in Civil & Environmental Engineering from UTK and upon graduation in December 2012 he will obtain his Master of Science degree in Environmental Engineering/Water Resources from UTK as well. His current plans include moving back to Memphis where he plans to start work at his hometown utility company of Memphis Light, Gas & Water (MLGW).