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Tools for water level management in flood control reservoirs

By

Ethan B. Mower

A Thesis
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in Wildlife and Fisheries Science
in the Department of Wildlife, Fisheries, and Aquaculture

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Tools for water level management in flood control reservoirs

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Flood-control reservoirs experience water level fluctuations that control survival of their biota. I explored diverse but related aspects of water-level management. Three frameworks were indentified for directing rule curve (i.e., daily targets for water levels) changes in flood-control reservoirs managed by the U.S. Army Corps of Engineers (USACE), with differing scopes and requirements. Framework choice depends on the reservoir's primary authorization and magnitude of the contemplated change. Changes without congressional approval must be based on flood risk. Quantile regression was used to model a maximum water level with a user-specified level of risk. Because actions that request changes to water levels from natural resource professionals should have a sound ecological basis, I analyzed the relationships between water level fluctuations and vegetation in reservoirs. Remote sensing methods were used to calculate a greenness index from vegetation in the reservoir based on 14 years of satellite imagery and water levels.

DEDICATION

To Diedre and Erik. It wasn’t easy, but you made it fun.

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CHAPTER I

INTRODUCTION

Background

Passage of the Flood Control Act of 1936 authorized impoundments on the Coldwater, Little Tallahatchie, Yocona, and Yalobusha rivers in the Yazoo River Basin (Saikku 2006). The newly-created USACE impoundments were designed to retain water during key periods to curtail flooding risk to communities and farms downstream. Emphasis was placed on preventing floods in the Delta region of Mississippi. A specific way the USACE accomplishes this goal is through rule curves that mandate certain water levels at certain times of the year. A rule curve mandates daily water elevations in the reservoir and dictates amount of water held for storage and released on a seasonal basis. In the above-listed reservoirs rule curves mandate an annual drawdown in August-November to operate at reduced levels and capture potentially abundant precipitation in winter and early spring. After the rainy season, reservoirs are permitted to refill to normal levels providing water storage for multiple uses. Reservoirs are typically divided into four different pool levels. Minimum pool, sometimes called dead storage, is the level at which no withdrawals can be made. Most of the impoundment would be dry at this level and this depth often reflects the lower elevation of outflow gates. Conservation pool, also referred to as summer pool, is the storage used for multipurpose management (e.g., recreation and wildlife uses). This pool can vary seasonally as a function of water demand and flood risk. This pool is often highest during summer (hence the term summer pool), and low during winter to increase flood pool capacity (figure 1.1). The lowest level often occurs during winter and at this period is often referred to as winter pool. Flood pool is the level used for increases above conservation pool level during the high precipitation season. Water in this level typically is lowered as soon as possible after a flood event. Often there is also a surcharge pool or backup pool to contain flood levels past flood pool capacity. Maximum water surface or freeboard is the level at which the water begins to overtop the spillway during the wet season (Wurbs 1991). Optimal flood management seeks to maintain an empty reservoir during the flood season to anticipate and subsequently accommodate the maximum recorded flow in that watershed. Following the flood season, the reservoir is allowed to refill to conservation pool levels.

Impoundments in the U.S. have long provided economic, recreation, and natural resource benefits. Reservoirs, lakes, and ponds represent a substantial portion of freshwater fishing, which attracted 37% of all freshwater anglers in 2011 (U.S. Dept. of Interior 2011). Reservoirs also provide large economic benefits associated with fishing. In a study of the economic impact of two flood-control reservoirs in Northern Mississippi, Hutt et al. (2013) estimated a total impact of approximately 8 million dollars on the local economy.

Despite the importance of reservoir fisheries, water level operations are dictated by one or several congressionally mandated primary purposes. Disagreements often arise between reservoir managers who maximize for the primary purpose and managers tasked with maximizing fish and wildlife resources. These disagreements arise because natural resource managers are charged with managing a resource without having the ability to manage its habitat. Communication between different managing agencies is often impeded due to the lack of knowledge about agency policies concerning changes to operations and lack of methods in estimating biological parameters under a risk-based framework.

Purpose of Study

The goal of this study was to provide tools needed for natural resource managers to be better informed about water level management in flood control reservoirs operated by the USACE. Many of the procedures and requirements for water level management are not clear to non-USACE personnel. My objectives were as follows: (1) to review policies and laws the USACE considers in developing and amending rule curves that govern water levels in flood control reservoirs; (2) estimate flood risk caused by altering rule curves in reservoirs; and (3) assess temporal development of wetland vegetation in a Mississippi flood-control reservoir to study impact of multiple water level regimes on vegetation abundance. This thesis is organized into three main chapters that are intended for publication in different journals. The citation format differs for each chapter, reflecting requirements of different journals. Throughout the thesis references are made to online engineering materials published by the U.S. Army Corps of Engineers. Due to the requirements of the target journals, these materials are not included in the references at the end of the chapters as the information can be found online at http://publications.usace.army.mil/publications/.

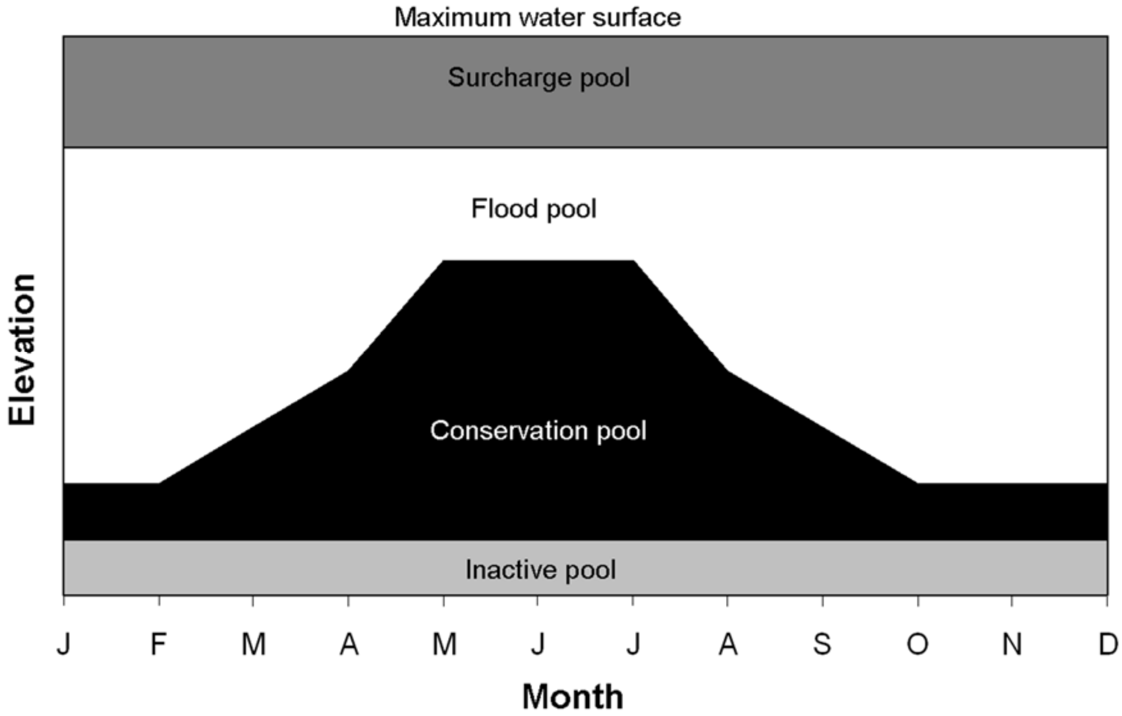

Figure 1.1 Pool levels defined by Wurbs 1991

Inactive pool is the level at which no withdrawals can be made. This is typically defined by the lower limits of the intake gate. Conservation pool is storage used for multipurpose management. And it fluctuates through the year. Flood pool also fluctuates through the year. Early in the year the storage allocated to flood mitigation is quite large to prepare for anticipated flood events. As precipitation likelihood decreases, more storage can be allocated to multiple-use in the conservation pool. Surcharge pool is backup storage that can hold higher then anticipated inputs to the reservoir. Maximum water surface is the point at which the water begins to overtop the dam or spillway.

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CHAPTER II

RULE CURVES IN FLOOD CONTROL RESERVOIRS: A HISTORIC AND PROCEDURAL ANALYSIS

Introduction

Reservoirs are a valuable resource in the United States, with nearly every major river impounded somewhere along its reaches (Dynesius and Nilsson 1994). Reservoirs greater than 6 hectare-meters number in the tens of thousands nationwide, and were constructed mainly in the twentieth century, with only limited construction in the last two decades (USACE 2009). Large reservoirs (greater than 61 hectare-meters) were constructed for various purposes including flood control, hydroelectric power, water supply, navigation, fish and wildlife habitat, recreation and others (Kennedy 1999). Commonly, reservoirs are managed for multiple purposes, requiring a balanced approach to water storage and withdrawal to satisfy the requirements of conflicting purposes.

Allocation of water storage volume to meet purposes for which a reservoir is operated is commonly regulated through schedules that guide reservoir volume and water level, often called rule curves. Such curves, which are based on analyses of historic hydrological conditions, prescribe reservoir daily target volume or water level throughout the year. Thus, rule curves dictate when water should be stored and discharged from a reservoir (Figure 2.1). Rule curves potentially have major impacts on water level, discharge, hydraulic retention time, biotic characteristics, and recreation. Because rule curves are designed to balance the multipurpose use of a reservoir, they are often controversial. Rule curves at Lake Lanier and John H. Kerr dams, both in the southeastern United States are involved in litigation regarding water allocation. Lake Heron and other reservoirs on the Rio Grande River in New Mexico are also involved in litigation concerning endangered species. Main-stem Missouri River reservoirs have been in litigation for many years over navigation and environmental issues.

The U.S. Army Corps of Engineers (USACE) administers water storage, use, and discharge in many reservoirs nationwide. Water management goals depend on each reservoir's purpose, although USACE reservoirs are generally multipurpose and consider fish and wildlife habitat and recreational opportunities as ancillary goals. Whereas the USACE's mission statement includes wildlife and environmental goals, traditional emphasis has been on the original authorization of the water development project (e.g., navigation, flood control), with additional emphases often added after construction. The process used by the USACE to establish and amend rule curves is not well publicized, and thus, is little understood by the public using the resource or affected by its discharges; by outside agency personnel charged with overseeing water quality, wildlife, and recreational needs; and even by some managers within the USACE. As a result, periodically there are questions and misunderstandings about the rule curve and how it might be amended under various management scenarios.

Given this lack of understanding, I believe the process the USACE follows to amend existing rule curves needs clarification. The general perception of the public and USACE personnel towards amending rule curves is that "it would take an act of congress" to make a change. This perception may or may not be accurate. Clarification could promote productive cooperation among USACE personnel, natural resource managers, and the public. To this end, I sought to review the policies and processes involved in amending rule curves by the USACE. I used flood control reservoirs in the Yazoo River Basin in north Mississippi as models. I base the review on scientific literature, legal literature, and interviews with USACE personnel.

Brief History of the USACE

The USACE was established during the Revolutionary War as a technical support unit to the U.S. Army. Its mission has evolved to include technical support to the army during war and peacetime, domestic economic development missions, and disaster mitigation (USACE 2012). The USACE originally took authority for domestic water resource development from the commerce clause in the U.S. Constitution (Gibbons vs. Ogden; Ballweber 1995). Navigation projects in the early 1800's were some of the first activities accomplished by the USACE, focusing on domestic water development on the Ohio and Mississippi rivers, using commerce as justifying authority. Subsequent legislation extended the scope and magnitude of the USACE mission (i.e., General Survey Act of 1824, River and Harbor Act of 1899, Flood Control Act of 1928 and 1936), eventually leading to a civil works mission. Authorization for many existing water development projects administered by the USACE comes from the Flood Control Acts of 1928 and 1936.

History of the Yazoo Basin Reservoirs

During the middle and late 1800's individuals were responsible for the protection of their lands from flooding. This led to a system of uncoordinated and inadequate levees that often failed and were scattered throughout the delta region (Arnold 1988; Saikku 2005). Passage of the Swamplands Act of 1849 and 1850 which ceded federal land to the state provided that the profit from sales be allocated for flood control. Increased land speculation and agricultural settlement in the region resulted from vast amounts of land divested by the federal government. An attempt at coordinating a statewide levee program to protect this flood-prone land was made in 1858, however poor planning, record floods, the civil war, and lack of funding reduced implementation and effectiveness of this effort (Pearcy 1991; Saikku 2005). Levees were the only flood-prevention measure implemented along the Mississippi River for many years. A series of heavy rains in the early 1900's broke many levees repeatedly and prompted the reevaluation of current practices and addition of other options. The record Mississippi River flood of 1927 was the impetus for a more comprehensive flood control plan with increased federal involvement. The Flood Control Act of 1928 was passed in response to the 1927 flood and authorized surveys of the Mississippi and Sacramento Basins for hydropower, irrigation, navigation and flood control (U.S. House of Representatives (a); Flood Control Act of 1928). These surveys were known as "308 reports." This act and the 308 reports became the framework of most future flood control efforts and appropriations.

The 308 survey for the Yazoo Basin was published in 1934 and recommended against any system of reservoirs being built in the area (House of Representatives (b)) due to an insufficient cost benefit ratio. The reservoirs would have cost $48,000,000, and only reduced flood stage at the Vicksburg gage 6 inches at maximum. No significant irrigation benefits were identified. The report acknowledged that the cost of the project would not be justified “in the present time nor in the prospective future.” The report recommended a continued state effort for the local overflow problem. This decision was consistent with Congress’ attitude at the time to deny projects that had only local benefits. Two years later, in 1936 the projects were approved with pressure from Will Whittington, a congressman from Greenwood, MS (Reuss 1982; House of Representatives (c); U.S. Senate (a)). The reversal of position can be attributed to political maneuvering by Whittington, and an intense desire from congress to fund reservoir projects. In fact, the Flood Control Act of 1938 which was passed almost unanimously in the house and senate committed the federal government to pay for all reservoir construction costs where previously local contributions had been required (Pearcy 1991). The Yazoo reservoirs were authorized under the justification of employment, although the primary purpose listed in the law was for flood control (Flood Control Act of 1936). The reservoirs were exempted from the typical cost-sharing requirement based upon the already economically poor region and the nature of the annual floods in the delta (U.S. House of Representatives (c); U.S. Senate (a)). The dams first functioned as a fixed outlet, meaning that the USACE took no active management for water levels (USACE, personal communication, February 2012). The rule curves have been modified several times since these reservoirs were constructed (Figure 2.1) to balance agricultural, flood control, recreational, and fisheries interests (USACE unpublished report).

Alternatives for Amending Rule Curves

Reviews of the scientific literature, legal literature, and interviews with USACE personnel revealed three potential options for amending rule curves, each with a unique process and scope. These options are designated by the labels *general investigations*, *continuing authority program*, and *water control plan*. Each of these options is reviewed below.

General Investigations

The general investigation (GI) process is used to authorize a new USACE project, major reoperation studies, or reallocation study, which often can require amendments to rule curves. A GI is composed of three phases including reconnaissance, feasibility, and design and implementation (Figure 2.2). The GI process is initiated and authorized by the U.S. Congress to investigate the feasibility of solving a water resource problem with federal funds. The GIs have historically been authorized in flood-control acts. If a study was previously done, but no construction occurred, a resolution may be passed to review the project without a new GI (Maass 1950; Carter & Stern 2011).

A reconnaissance phase, which includes a reconnaissance study, identifies a water resource problem and determines if the federal government has a legitimate stake in addressing it. Federal interest is determined mainly by a cost/benefit analysis corresponding to seven main missions of the USACE: navigation, flood control, ecosystem restoration, hurricane and storm damage reduction, water supply, hydroelectric power, and recreation (engineer regulation1105-2-100). However, there have been many times when a project was authorized in the face of a less desirable cost/benefit analysis, often justified through employment benefits or local hardship. The Yazoo Basin reservoirs had undesirable cost/benefit ratios, but these projects were authorized because of the enhanced employment opportunities it provided in the region (U.S. Senate (a)).

A reconnaissance study is 100% federally funded up to US $100,000, identifies a non-federal cost-sharing sponsor and specifies a federal cost-sharing agreement for an upcoming feasibility phase (Wigington et al. 2007; Carter & Stern 2011; engineer regulation 1105-2-100). The requirement for becoming a non-federal sponsor, outlined by 42 USC §1962.b, is that the sponsor must be a legal public body or non-profit entity with the ability-to-pay for their part of the project cost share. The reconnaissance study typically takes one year, and results in a 905b report that details the cost to the federal government and level of federal interest (engineer regulation 1105-2-100). The Secretary of the Army, who acts through the Chief of Engineers, decides if the study continues on to a feasibility phase (public law 99-662 §905(b)). Public input periods are crucial at this stage and are a required component. Third-party quality control of decision documents and National Environmental Policy Act (NEPA) compliance are also required.

Following a positive recommendation from the 905b report, the Secretary of the Army approves moving on to the feasibility phase which includes a feasibility study. The purpose of the feasibility study is to identify all potential solutions to the water resource problem, identify all environmental impacts, make plans for building structures, and analyze cost/benefit ratios for the proposed solutions. All USACE planning studies follow a six-step process outlined in a planning and guidance framework. It is beyond the scope of this review to explain this six-step process, but the feasibility study must compare alternative plans, coordinate with appropriate agencies having a stake in the project, and the plan selected must maximize either the National Economic Development or the National Ecosystem Restoration.

This feasibility study is cost-shared 50% federal funds, 50% non-federal sponsor (public law 99-662 §105(a)) and is conducted by the USACE district in which the proposed project is located. The agency requesting the change is charged with finding a non-federal sponsor with the ability-to-pay for the cost-share, whether it is itself or an appropriate non-federal entity. If the project involves one of the original Mississippi River and Tributaries Projects, the report is submitted to the President of the Mississippi River Commission, otherwise the report is submitted to the division commander and eventually the Secretary of the Army (engineer regulation 1105-2-100). The NEPA impact statements are finalized in this phase and either an Environmental Assessment/Finding of No Significant Impact or an Environmental Impact Statement is also required during this phase (USACE personal communication, February 2012). This phase may require 2-3 years for completion. The feasibility report is the foundation upon which Congress approves the recommended solution to the water resource problem. Upon approval of the feasibility report by Congress, the project engineering, design, and construction phase can begin, pending appropriations. Because structural changes are not commonly required for an amendment to a rule curve, this process is not described in detail within this document.

The GI is a well-defined process by which rule curves can be amended through congressional approval. Section 216 of the River and Harbor Act of 1970 identifies a GI as an avenue for reevaluation of projects due to “significantly changed physical or economic conditions” (public law 91-611). However, it is a long, expensive process, going through Congress and appropriations twice. John H. Kerr Reservoir in North Carolina and Virginia, and Philpot Reservoir in Virginia are undergoing a section 216 GI at an approximate cost of $5 million and $2 million, respectively. The master plan for the Missouri River basin is also being updated through a GI at a cost of approximately $11 million (USACE personal communication, February 2012).

Continuing Authority Program

Many USACE activities and projects are not large enough in scope for congressional attention. Generally, when a need for a change in a project is identified, studies can be performed to analyze the feasibility of such a change through already existing authority "to the extent possible" (engineer regulation 1165-2-119). Otherwise they are done through a GI. Projects authorized under a continuing authority program (CAP) circumvent Congress and appropriations and use existing authority to accomplish the goal. The USACE has a special annual fund for CAP projects that is available every year, and CAP projects are approved by the division commander. Only specific activities are eligible for authorization under CAP. These activities include erosion stabilization, navigation improvements, sediment/dredge material management, flood control, aquatic ecosystem restoration, snagging, and project modifications for improvement of the environment (Carter & Stern 2011; engineer regulation 1105-2-100). The latter activity will be best suited for amending rule curves in existing reservoirs.

Authority for modifying projects to improve the environment is provided through section 1135 of the Water Resource Development Act of 1986 (public law 99-662 §1135, 33 USC §2309(a)). Expenditures for this type of project are capped at $5 million. All lands, easements, rights-of-way, relocations, and dredge material are to be provided at no cost by the non-federal sponsor. Any cost of operations, maintenance, repair, replacement, and rehabilitation (OMRRR) that could potentially be necessitated by an amendment to the rule curve are to be assumed by the non-federal sponsor after the project is constructed (Carter & Stern 2011; engineer pamphlet 1165-2-1). Initiating a CAP section 1135 study requires sending a letter to the district commander from an appropriate non-federal sponsor stating an interest in participating in a CAP section 1135 study to resolve a water resource problem. The division would then opt to initiate the required studies.

The section 1135 process follows two phases - a feasibility phase and a design and implementation phase (Figure 2.3). The feasibility phase has two main purposes: it determines the federal interest in the proposed project, and provides opportunities to formulate alternative solutions to the identified problem (engineer regulation 1105-2-100). A report analogous to the 905b report of a GI includes a justification of the project, legal sufficiency, impact analyses (e.g., NEPA), real-estate plans, sponsor financing plans, cooperation requirements with local interests, and OMRRR plans.

If the project feasibility phase can be executed for less than $100,000, it can be entirely federally funded and no CAP federal cost-share agreement is needed. The division commander approves the feasibility phase via a decision document stating whether the project should continue to the design and implementation phase. As with a GI, the project must optimize the National Ecosystem Recovery or National Economic Development goals. However, waivers can be submitted to deviate from these requirements if there is strong justification for a locally-preferred-plan.

Upon approval of the feasibility phase by the division commander, the project may move into the design and implementation phase. Project construction that could possibly be related to amending a rule curve would be cost-shared through 50% federally funded allocations and 50% non-federally funding by the requesting agency or appropriate non-federal sponsor. The construction process follows the guidelines for construction of an individually authorized project (i.e., GI). It would not be common to make structural changes to a project for an amendment to the rule curve. Thus, the design and implementation stage will not be described in detail within this study. The reader is referred to engineering manual 1105-2-100 for more information about the construction process.

This section 1135 process may be simplified at any point at the discretion of the division commander if the failure of the project will not result in loss of human life (engineer regulation 1105-2-100). The process seems ideal for modifying a rule curve in an existing flood control reservoir, which would require extensive flood-risk based evaluations. However, internal guidance states that the CAP is not to be used for studies, only "activities" (engineer regulation 1105-2-100). It is not clear if a rule curve amendment would constitute an activity, as this approach has probably not seen much use for a non-structural request. Studies would need to be done and it is not clear whether these would be covered under the CAP process. It is conceivable that an amendment would be an activity. Engineer regulation 1105-2-100 states the purpose for this 1135 authority includes "modification of structures *and operations* of water resource projects" (italic emphasis added), suggesting amending a rule curve falls under its purpose. The issue of whether amending a rule curve constitutes an activity may require clarification at a general policy level or by a ruling from a federal court as the result of litigation. Another problem with this approach is the enormous backlog of CAP requests. Section 1135 CAP requests total $41 million in backlogged projects, with additional current projects often spilling into funding allocations for upcoming years (Carter and Stern 2011). Because of this backlog, amending rule curves through Section 1135 CAP requests could take years.

Water Control Plan

A third option for amending rule curves is changing the Water Control Plan (WCP). This type of action is acceptable to optimize the project for general authorities passed subsequent to the original authorizing act (engineer regulation 1110-2-240; engineer pamphlet 1165-2-1). A list of these general authorities is provided (Table 1.1).

The broad spectrum of USACE projects often requires specific seasonal or even daily water storage and release targets. Coordination of these activities within individual reservoirs and among multiple reservoirs to achieve management goals constitutes a WCP. Physical execution of the WCP is often detailed in a separate Water Control Manual, containing specific instructions for project operation.

A WCP includes a summary of location, description, authorization, and purpose of individual or multiple reservoirs. Baseline meteorological and hydrological conditions, water quality, runoff and flood stage information are also found in a WCP. Additionally, a WCP contains detailed information on objectives, benefits, and constraints of the overall purpose of the WCP. Plates detailing structures, project area, rule curves, hydrographs, discharge ratings, frequency and duration curves for water control points are included in the WCP (engineer regulation 1110-2-3600; engineer regulation1110-2-240). The WCP provides plans for day-to-day operations management.

In accordance with the Water Supply Act of 1958, WCPs are mandated to be updated periodically to keep them applicable to social, economic, and physical conditions (public law 85-500). The purpose of modifying a WCP is to enable a reservoir to run efficiently (engineer regulation 1110-2-240; engineer manual 1110-2-3600). Modifications are typically proposed and researched at the district level and approved by the division commander (engineer regulation 1110-2-240). This process differs from the CAP program in which program proposals and research must occur with division oversight and from a GI in which approval is required from the Secretary of the Army and ultimately, the U.S. Congress. Unless initiated by the USACE, a letter must be sent to the USACE from an appropriate non-federal sponsor asking for a re-evaluation of the water control plan (USACE 2001). The process of revising a WCP is vague, due to the diversity of USACE projects (Figure 2.4). NEPA analyses, public comment, coordination with appropriate agencies, alternative plans and decision records of all studies performed seem to fulfill most requirements for a WCP update (engineer manual 1110-2-3600; engineer regulation 1110-2-240; Wigington et al. 2007; USACE personal communication, February 2012). Some changes can be made through a categorical exclusion with minimal effort (USACE, personal communication, February 2012). A categorical exclusion enables an action that has no effect on the environment to be performed with any further impact analysis under NEPA (e.g., environmental assessment or environmental impact statement). USACE personnel were often found to deny the ability of an update to the WCP as a vehicle to change a rule curve (USACE personal communication, February, 2012). However, according to internal documents, rule curves are mandated to be updated along with the WCP (engineer regulation 1165-2-119; engineer pamphlet 1165-2-1; engineer regulation 1110-2-240).

Conclusions

This review has revealed that options do exist for altering rule curves in USACE reservoirs. The general investigation, continuing authority program, and water control plan are each feasible options to amend a rule curve, with the level of difficulty decreasing with each process, respectively. The CAP section 1135 and water control plan are little used, although potentially effective alternatives for amending rule curves.

Cooperation with resource professionals varies widely among USACE districts. Judging from interviews with USACE personnel, it is apparent that most districts and higher level USACE officials were hesitant to consider the possibility of amending reservoir operations without congressional approval (i.e., GI option), but some executive personnel were open to the possibility. Flatt and Tarr (2011) conducted a legal review of the flexibility potential of the USACE to amend operations in the face of changing environmental conditions. They found that the legal system in which water development laws were passed originally intended to promote flexibility in the process where rigidity is now found. Customary decisions and historical activity may play a more significant role in determining operating procedures in water development projects than does an interpretation of the current legal framework.

One of the major roadblocks to exercising the flexibility originally intended is the language found in many laws stating that operations can be modified provided they do not “significantly” alter the original authorization. Significance is not defined in those laws. This lack of definition from Congress does enable the protection of the *chevron* doctrine. *Chevron* doctrine, used in court, affords federal agencies the benefit of the doubt when they interpret vague and conflicting legislative requirements (Stewart 1975;

Ballweber 1996; Flatt and Tarr 2011). The USACE does interpret conflicting requirements in balancing uses from multiple stakeholders and requirements from multiple laws and thus they would be entitled to such protection.

Laws and policies that create the framework for the current USACE civil works programs are convoluted, a patchwork, and are sometimes conflicting (Whisnant et al. 2009). These laws and policies are often subject to individual interpretation in decision making, which is in turn subject to judicial review. Hence, USACE personnel may be hesitant to try new and untested procedures to accomplish a change in reservoir operations. This review is not intended as a “silver bullet” to cut through current political and procedural avenues. Amending rule curves involves many stakeholders with many competing interests often regarding old projects. Tradition and original purpose require serious consideration and should not be taken lightly. However, this review provides an improved understanding into the processes required for a management action often desired by fishery managers or other users affected by rule curves. Having clear alternatives and encouraging flexibility in reservoir operations to change rule curves should promote productive communication and cooperation between USCAE, resource management agencies, and multiple stakeholders.

Table 2.1 List of general authorities applying to all USACE projects

General Authority	Name of Act	Public law#
Recreation	Flood Control Act of 1944	79-534
Municipal and Industrial Water Supply	Water Supply Act of 1958	85-400
Fish and Wildlife Conservation	Fish and Wildlife Coordination Act of 1958	85-624
Water Quality	Clean Water Act of 1972	92-500
Endangered Species	Endangered Species Act of 1973	93-205

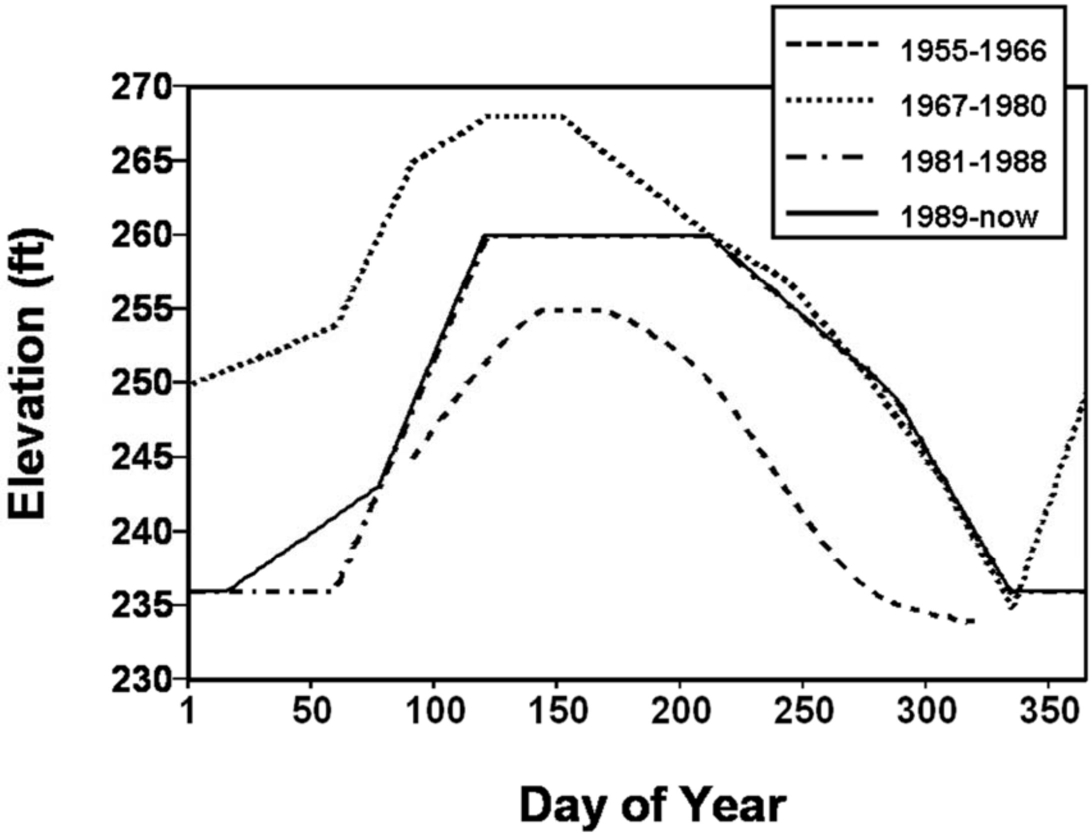

Figure 2.1 Rule curves applied to Sardis Reservoir in the Yazoo River Basin, Mississippi, USA.

The first curve was established in 1955; information for this rule curve was available only for April 1--- November 15 period. Elevation is in reference to mean sea level. Rule curves applied to the other three reservoirs mentioned in this study are similar to those of Sardis Reservoir.

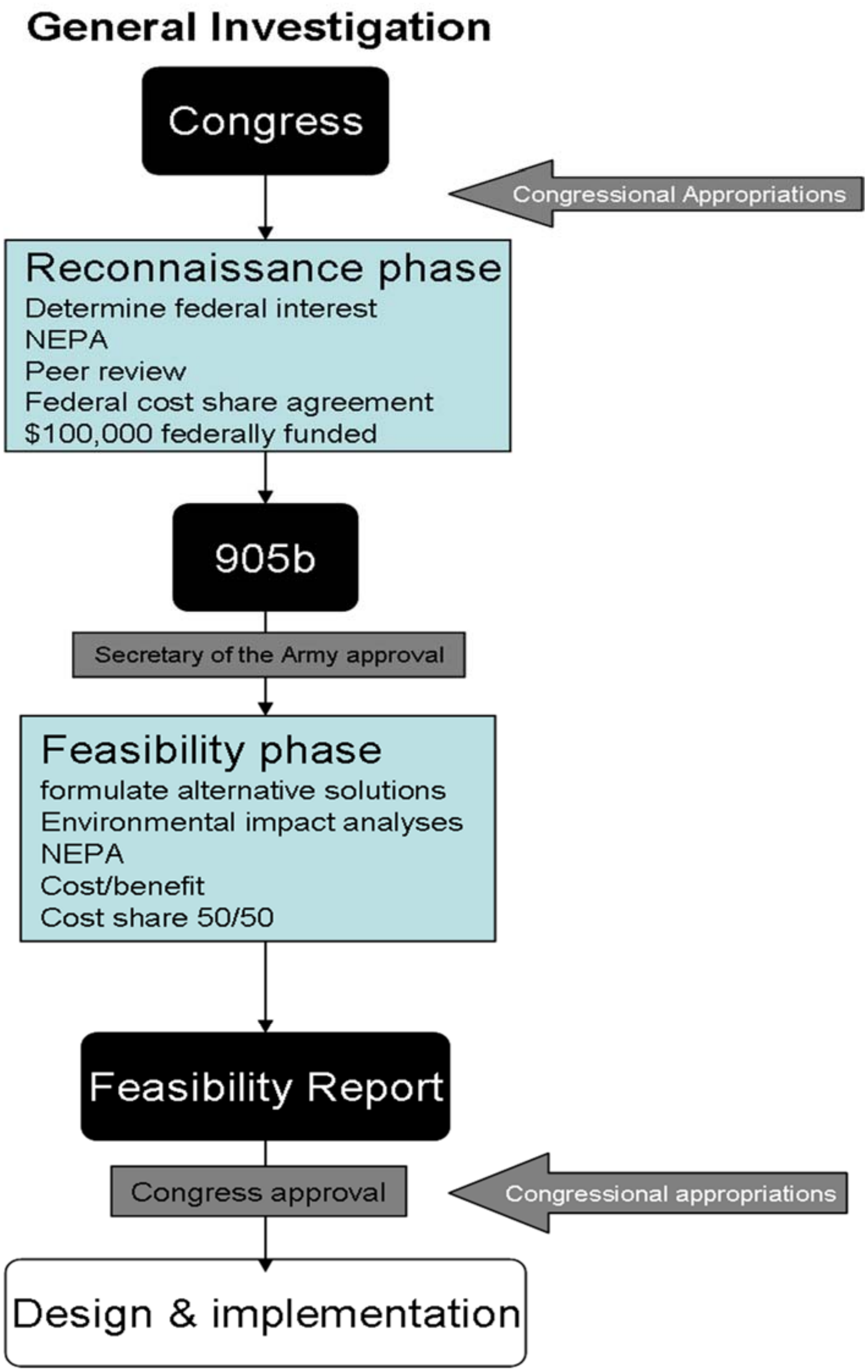

Figure 2.2 Flowchart for the *General Investigation* process

This process is typically used for new projects, amending existing projects due to changed conditions, or reallocations in water use, and historically has been applied to flood control acts.

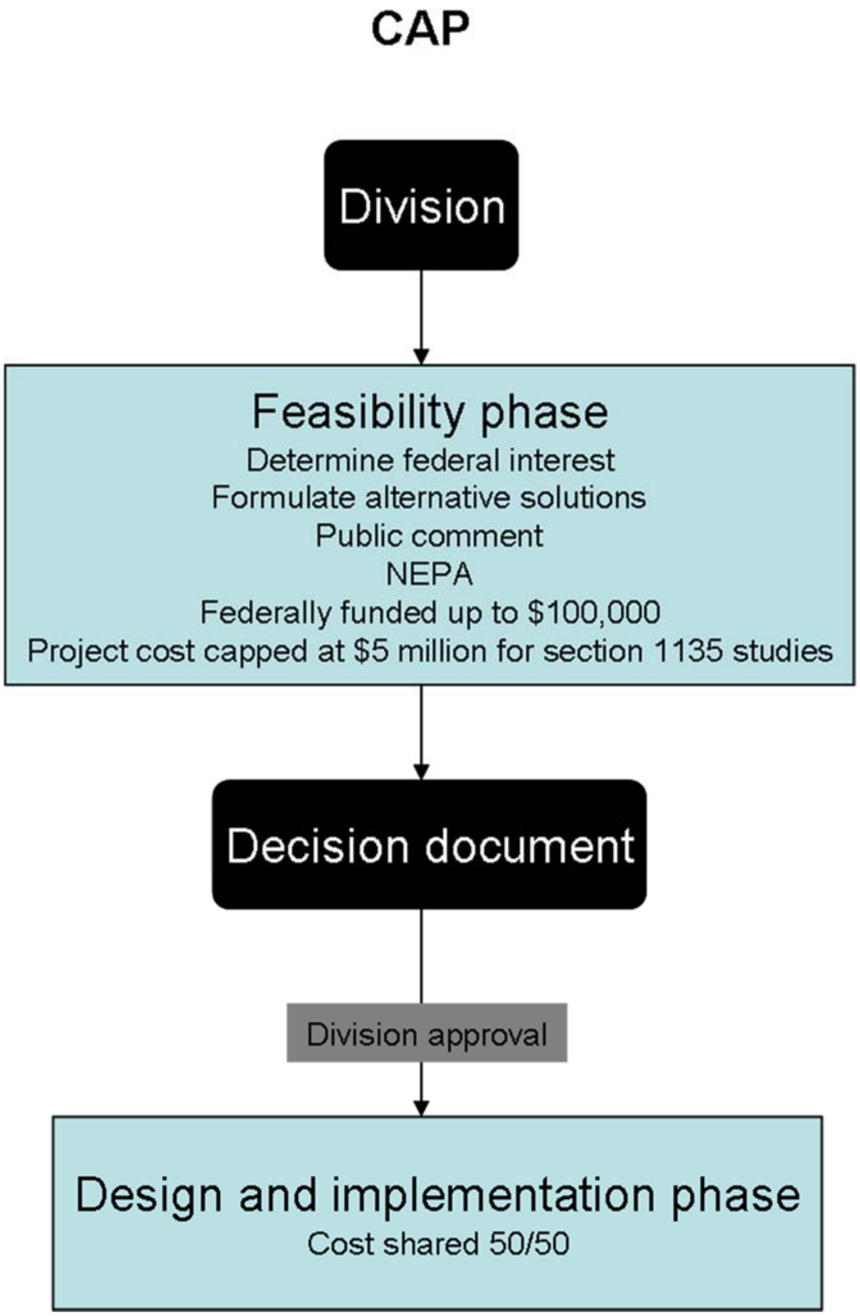

Figure 2.3 Flowchart for the Continuing Authority Program.

Many USACE activities and projects are not large enough in scope for congressional authorization. Only erosion stabilization, navigation improvements, sediment/dredge material management, flood control, aquatic ecosystem restoration, snagging, and project modifications for improvement to the environment are eligible for authorization.

References

Reference styles may be of your choosing whether APA, MLA, or any other, so long as it is applied consistently throughout the references section.

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CHAPTER III

A BASIC METHOD FOR EVALUATING RULE CURVES

Introduction

Large impoundments in the U.S. were mostly authorized in the middle to latter half of the 20th century, often reflecting public demands for flood control, irrigation, and opportunities for recreation (Miranda 1996). Changing factors such as economics, social, and environmental conditions, as well as changing values can often result in requests for reservoir managers to change seasonal water storage to best suit these needs. If changes are to be made however, they must be based on the original authorization for the project. In reservoirs authorized for flood control for example, changes must consider flood-risk (U.S. Army Corps of Engineers, UASCE, Engineering Pamphlet 1165-2-100). To facilitate this process, methods that guide optimal changes relative to project purpose framework (e.g., hydropower, flood risk, recreation) are becoming more common in the literature as the demand on water resources increases (Wurbs 1991; Kirby 1999; Labadie 2004; Rani and Moreiera 2009). Information on climate change is becoming more quantitative and accessible and also serves to focus attention on efficient methods of anticipating operational changes (Farley et al. 2011).

Seasonal management of reservoir water levels is typically managed through a schedule that dictates the timed release of stored water. Seasonal goals for water levels minimize flood risk and often are established according to a historical analysis of regional climate and hydrology. Seasonal goals are compiled into a rule curve which is a graphical representation of water storage and release relative to day of the year. To develop rule curves, water managers use simulation models that incorporate historic stream flow and precipitation data to predict maximum flood events. These models typically require complex software and multiple hydrologic variables to be accurate. Alternative methods for modeling flood risk include optimization models that contain linear, non-linear, and dynamic programming. Genetic algorithms and neural-networks are becoming more common in reservoir optimization (e.g., Yeh 1985; Wurbs 1991; Labadie 2004). Because of the complexity of these modeling techniques, developing rule curves is generally left to the civil engineers who design and manage the project.

Rule curves can have important influence in structuring fish communities (Sammons and Bettoli 2000; Dagel and Miranda 2012). Personnel tasked with managing reservoir fisheries often have to explain water levels to the public, or recommend changes to the rule curve, yet they may not have access to the information or tools used to develop a rule curve. This lack of control stems from distinct jurisdiction separation between the water and fisheries management agencies, limited data availability for fisheries managers, complicated engineering software, and a general lack of engineering experience to model changes to a rule curve in a flood-risk framework. A lack of simple methods to explicate rule curves and to assess consequences associated with a hypothetical change in the rule curve or climate patterns can prevent a manager’s ability to present detailed, realistic, and viable water level options for discussion. To address this need, I developed a procedure that fishery managers can use to visualize flood risk associated with changes in the rule curves. I demonstrate usefulness of the model using a reservoir operated for flood control. I also demonstrate how rule curves may require amendments to accommodate potential changes in precipitation that might result from detectable climate changes.

Methods

I estimated seasonal water volume changes using the long-term daily reservoir water-level. Changes in water volume were documented for periods of *n* consecutive days. The distribution of changes were examined relative to day of the year (DOY), and a trigonometric polynomial model was assembled to represent the relationship between the magnitude of volume changes and DOY. The model was used to estimate the maximum allowable water level that would absorb volume increases and minimize the risk of spilling for each day of the year. This estimated maximum water level was considered a risk-based rule curve.

The procedure was implemented with long-term water level data for Grenada Lake, Mississippi. This 14,000-ha reservoir was impounded in 1954 and is operated primarily for flood control by the U.S. Army Corps of Engineers. Water levels in the reservoir vary an average of 6 m annually and follow a rule curve established by the USACE. Daily water levels since 1955 were available for download from www.rivergages.com. Occasional missing values were estimated using the two nearest adjacent values; for multiple missing values, a gradient was created between the two nearest adjacent values.

Water level data were used to compute daily and period changes in volume. Volume was estimated with an equation derived from an elevation-volume chart available for the reservoir. Daily volume change was computed as the difference in volume between day *i* and day *i*+1. Period volume change was defined as the maximum increase over an *n*-day period long enough to encompass most prolonged water level rises that occur in exceptionally wet years. The *n*-d period was estimated by examining number of consecutive days water level rose in fall and winter, when water levels were expected to be either declining or maintained at conservation pool as the reservoir was prepared to accommodate winter and spring precipitation. Period volume change was computed as the moving sums of daily changes for *n*-day periods with the EXPAND procedure (SAS Institute, 2012) that generated backward moving sums, i.e., it added the daily changes occurring in a given day and *n*-1 previous days.

The resulting distribution of *n*-day volume changes were used to fit a model descriptive of the relationship between day of year (DOY) and volume increase. The precipitation patterns in northwest Mississippi show recurring annual cycles, although with inter-annual variability. Following precipitation cycles, *n*-day volume changes were usually least in July-August, increased in late fall and early winter, peaked in late winter and spring, and decreased through summer. I applied a trigonometric polynomial model to simulate cycles in volume changes (ΔV):

$$\Delta V = b_0 + b_1 \, cos(x) + b_2 \, sin(x) + b_3 \, cos(2 \cdot x) + b_4 \, sin(2 \cdot x) \qquad (1)$$

where,

b_0, b_2, b_3, b_4 = regression coefficients, and

x = 2·π·DOY/365.

In equation 1, $b_0 – b_2$ are sufficient to model a symmetric annual cycle, but $b_3 – b_4$ are necessary if the cycle is asymmetric. I fitted equation 1 with a quantile fit over the 97.5th percentile of the *n*-day volume changes (QUANTREG procedure, SAS Institute 2012), so that the predictive model encompassed nearly all of the water level rises experienced over *n* consecutive days in 1955-2010. Choice of the 97.5th percentile is justified below in the Results section.

The resulting quantile regression model was used to predict potential rises in water levels over *n* consecutive days relative to time of the year. The predicted *n*-day increase in volume was subtracted from the full volume of the reservoir at spillway elevation (i.e., 70.5 m) according to DOY. A safety buffer of one meter was used to modify the spillway crest to 60.5m. The estimated reservoir volumes were then translated into reservoir elevations with the volume-elevation regression model previously described. The resulting daily elevations represented an annual water level at which the reservoir level will not reach spillway elevation given an *n*-day rise. Thus, the risk-based rule curve represents the water level, by DOY, from which water level will not reach spillway elevation (97.5% of the time) given *n*-day water volume changes observed in 1955-2010. The SAS code used to generate the risk-based curve is provided in Appendix 1.

Climate change is closely linked to annual precipitation patterns and hence may need to be considered when planning reservoir operations. I investigated how climate change predictions may be used to anticipate potential adjustments to rule curves. Precipitation change predictions were obtained for the Grenada Lake watershed from the USDA Forest Service Eastern Forest Environmental Threat Assessment Center (Raleigh, North Carolina). Two different global circulation models were available including the Commonwealth Scientific and Industrial Research Organization Mark 3.5 model (CSIROMK3), and the Hadley Center for Climate Prediction and Research Mark 3 model (HADCM3). These models incorporate different assumptions about global emissions scenarios compiled by the International Panel on Climate Change. The CSIROMK3 model assumes a globally integrated society with a balanced emphasis on fossil resources. The HADCM3 model assumes more isolated societies that are environmentally friendly. I wanted to analyze precipitation data predicted for a period of two decades into the future, far enough to detect relevant change but not so far in the future for the results to lose prediction precision. The data predicted by these models were stochastic and distributed in 1-year intervals, so I averaged data points for 2027-2033 to represent an average. Predicted precipitation patterns were compared to baseline data averaged for 1981-2010 obtained from the PRISM climate group (Oregon State University, Corvallis). Changes in precipitation were represented as the ratio of the observed 1981-2010 mean precipitation and the predicted precipitation, computed monthly. The divisor of this ratio and the current rule curve would approximate the rule curve required to accommodate expected precipitation. For example, if the predicted precipitation for a month was 115 mm, and the observed precipitation was 118 mm, then 115/118 = 0.9746 reflects the change in precipitation during that month (i.e., precipitation coefficient). The rule curve then could be adjusted upward to accommodate this increase in storage capacity by dividing the water levels in that month by the precipitation coefficient. For example, if the rule curve specified a water level of 60 m on a certain day, then the adjusted value would be 60/0.9746 = 61.56 m. This method will result in a rule curve characterized by abrupt changes each month because applying a monthly constant value to all days within a year will change all values within each month equally. To approximate a more realistic curve, the resulting rule curve was smoothed by fitting equation 1 to the data (GLM procedure, SAS Institute 2012). The two resulting adjusted rule curves were compared to the current rule curve and the generated 97.5th quantile model (base model).

Results

Water level increases in Grenada Lake were highly variable due to the project's flood control purpose and annual fluctuations in precipitation. Since 1955, annual changes in water level have been as great as 14 m. Per day, water level increases have been as pronounced as 2.6 m and volume increases as great as 32,100 ha-m (Figure 3.1). Seasonally, water level increases peaked in December-May and dipped in July-September (Figure 3.1). Since the current rule curve was established in 1981, Grenada Lake exceeded the spillway crest 266 d out of 10,748 d, resulting in a flood risk of 2.5%.

The relationship between volume and water level derived from the elevation-volume chart was exponential. A log-log model fit to the data expressed the relationship between volume (V; ha-m) and water level elevation (E; m) as $\log_e V = -46.7 + 13.8 \log_e E$ ($r^2 = 0.985$). The exponential-shaped curve suggested that storage volume in every 1-m cross-section became progressively greater as water level increased.

After examining long-term water level rise events I selected 60 d as the *n*-day period. During 1955-2010, water level rises in fall and winter normally lasted less than 10 d, with 18 events lasting 10-30 d, 17 events lasting 31-60 d, and one event lasting 78 d.

The 60-d summations produced water level increases as great as 9.7 m and volume increases as great as 136,000 ha-m. The quantile regression fit a curve that adequately modeled the 97.5 percentile of the 60-d rises relative to DOY (Figure 3.2). The trigonometric polynomial model was significant statistically with b_1 - b_4 contributing to the fit (Wald chi square, $P < 0.01$). The curve was asymmetric rising slowly since late

December, peaking between DOY 125-135, and dropping sharply thereafter until DOY 250-270 before rising again.

Subtracting the predicted rise in volume from the reservoir total volume, and converting volumes back into elevations, produced the daily water levels at which the reservoir will not spill after a 60-d rise as large as the 97.5 percentile of all recorded water level changes (Figure 3.3). Moreover, any rule curve formulated to fall below the 97.5 percentile curve illustrated in Figure 3.3 would have a flood risk of less than 2.5%.

The two climate models predicted different seasonal deviations from current precipitation patterns. For the Grenada Reservoir watershed, and by 2027-2033, mean precipitation is predicted to increase by 2% according to the CSIROMK3 model, or decrease by 6% according to the HADCM3 model. Although the change in precipitation is not large, changes in the monthly distribution of the precipitation are evident (Figure 3.4).

Models plotted against the current rule curve follow the monthly distribution of precipitation (Figure 3.5). The CSIROMK3 model departs from the base model strongly in the spring and follows closely in late summer and fall. The HADCMB3 model follows the base model closely, exceeding the base model in late spring where precipitation was predicted to decrease (Figure 3.4).

Discussion

Models applied by engineers to develop rule curves are complex, requiring various hydrologic data including meteorological, topographical, stream discharge, water surface profile, and water demand (USACE Engineering Manual 1110-2-3600). In contrast, the model I applied requires only long-term water levels, which integrate many of the variables required by more complex models. Moreover, water level data integrate reservoir discharge patterns used by dam operators relative to day of the year and water level. A major drawback of this approach is that it requires a large data set of past water level records. This limitation precludes application to new projects or developing rule curves for forthcoming projects. However, for projects that have existed for several decades, this method provides a minimalist verification of existing rule curves and opportunity to explore alternatives capable of meeting water storage requirements as well as fish and fishery goals.

I expected the generated rule curve to approximate the current rule curve. However, there were some major differences as the current rule curve recommended lower water levels during most of the year, except in DOY 100-180 when the current rule curve allowed for a greater risk of spilling. The current rule curve takes the possible magnitude of those 2.5% possible flood events into account as “design floods” (engineering regulation 1110-8-2 (FR)). A design flood is a modeled flood event and is often a standard to which a reservoir is built. These flood events are often given occurrence probabilities based on number of years between events (e.g. 100-year flood). Whether the dataset included this design flood or not may partly explain the discrepancy between the two curves. This model is based on previous flood events that may or may not have been equal to the magnitude of the highest anticipated flood event for the reservoir, thus underestimating flood risk. One way of mitigating this uncertainty is adopting a more conservative rule curve. This can be accomplished by selecting a greater quantile in the quantile regression model (e.g., 99, 99.9), so that most all observed flood events are accounted for, although quantile regression on empirical data cannot account for rare flood events that have not yet been recorded.

Another option is to interpret the curve generated from observed quantiles as a ceiling or guideline to design a curve that would consider other water level needs for water level in addition to flood control. Thus, the curve generated from the quantile regression model does not constitute a hard target for a rule curve. Instead, it represents an umbrella under which adjustments can be made to accommodate various needs. For example, a rule curve may be established well below a reservoir's estimated capacity to absorb floods to facilitate access or to protect terrestrial vegetation that may be damaged by continuous or regular flooding. Similarly, although precipitation patterns may call for a shifting rule curve in certain time of the year to absorb floods, a stable water level may be required to allow boating or retain habitat for fish and wildlife. Any modification that stays beneath the guideline has a flood risk of less than the quantile specified in the regression model. A proposed rule curve may take on any functional form, so long as it stays under the specified flood risk depicted by the guideline.

Both climate models showed increases in precipitation in the latter half of the year, in some months quite drastically. The CISROMK3 model predicted a greater amount of change in the spring and winter, whereas the HADCMB3 model predicted small increases in spring and winter but mostly decreases. The precipitation increase in the fall and winter seems to be absorbed by the large volume available in the upper elevations of the reservoir (Figure 3.5), as evidenced by all three models following closely and approaching spillway crest in August-October. The HADCMB3 model followed the base model closely during most of the year, notably in the spring because the deviations in precipitation fluctuate closer to zero or even show a decrease. However, the CSIROMK3 model showed significant departure from the base model in spring. This departure from the base model is consistent with the predicted change in monthly distribution of precipitation (Figure 3.4) where the CSIROMK3 model predicts higher precipitation in the spring, during the time when total precipitation forces the reservoir to remain at a lower level where less storage is available.

Conclusion

Any modification to rule curves should be conducted within the framework of the original purpose of the reservoir. In federally-owned reservoirs, such as those managed by the USACE, rule curves may be congressionally mandated (Mower and Miranda, in review). In practice this means that while modifications can be made to reservoir operations, for a flood control reservoir, rule curve modifications must be made with flood risk as a primary consideration (USACE, Engineer Regulation 1165-2-119; Engineer Regulation 1105-2-100) and modifications may need congressional review and approval.

Fisheries managers are tasked with managing reservoir fisheries, and this often means making recommendations for modifying rule curves to benefit fish. Reservoirs which fluctuate seasonally can influence availability of fish habitat and the spatial and temporal connectivity of the reservoir to historic floodplain habitats, and have a substantial influence on diversity and abundance of fish assemblages (Slipke et al. 2005; Dagel and Miranda 2012; Miranda et al., in press). This method allows fisheries personnel to contemplate possible modifications to the rule curve that may benefit fish and fishing access, while staying within a specified flood-risk framework. Knowledge about flood risk associated with a proposed change is crucial to the collaborative process between reservoir fisheries personnel and reservoir engineers. This method is not intended as a replacement to more rigorous and conventional modeling techniques. Rather, this technique provides managers with knowledge intended to improve communication and planning between biologists and engineers.

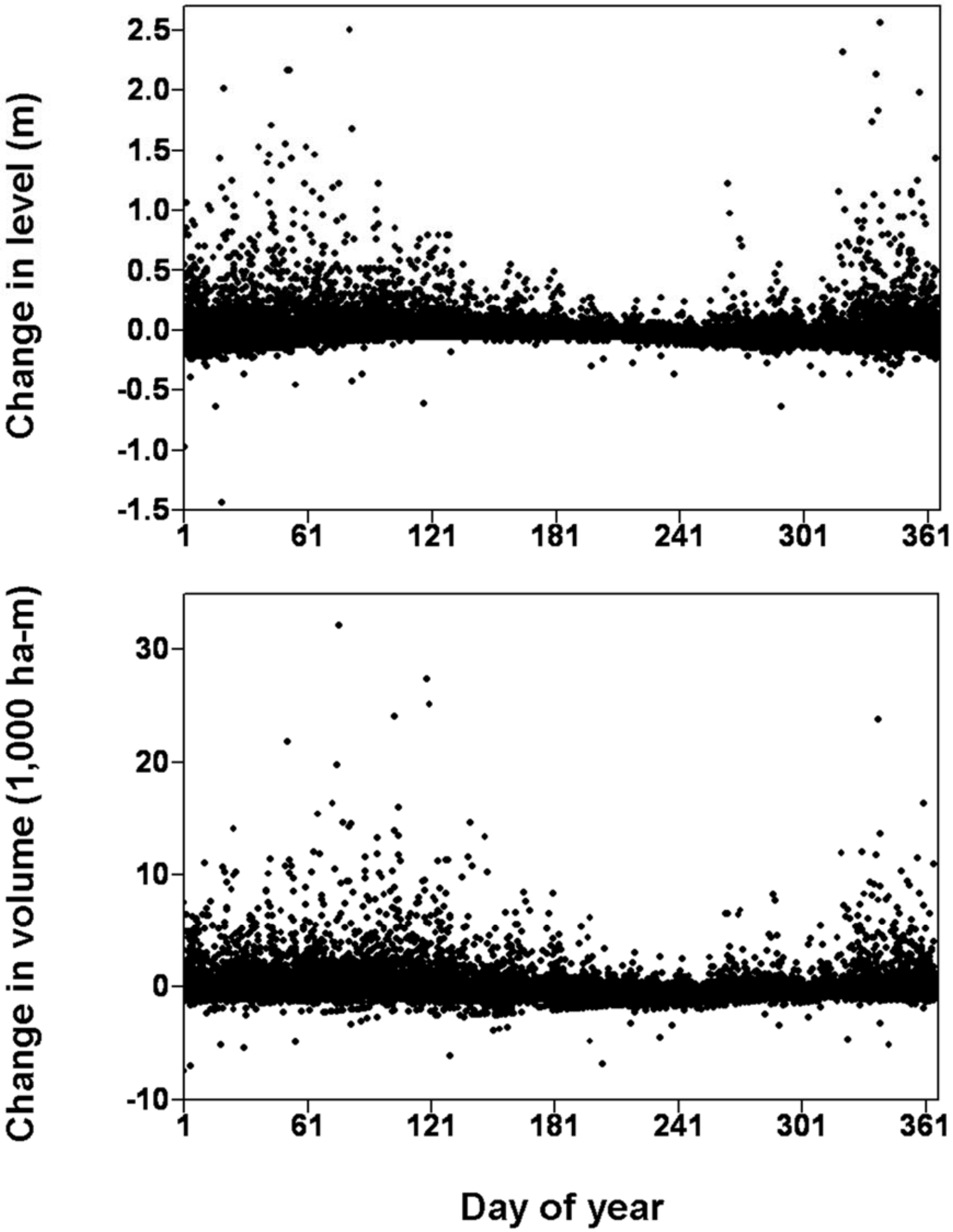

Figure 3.1 Seasonal distribution of 1-day water level and volume increases from Grenada reservoir

Increases from 3, 7, 14, and 30 day moving averages show the same seasonal pattern with an increased scale.

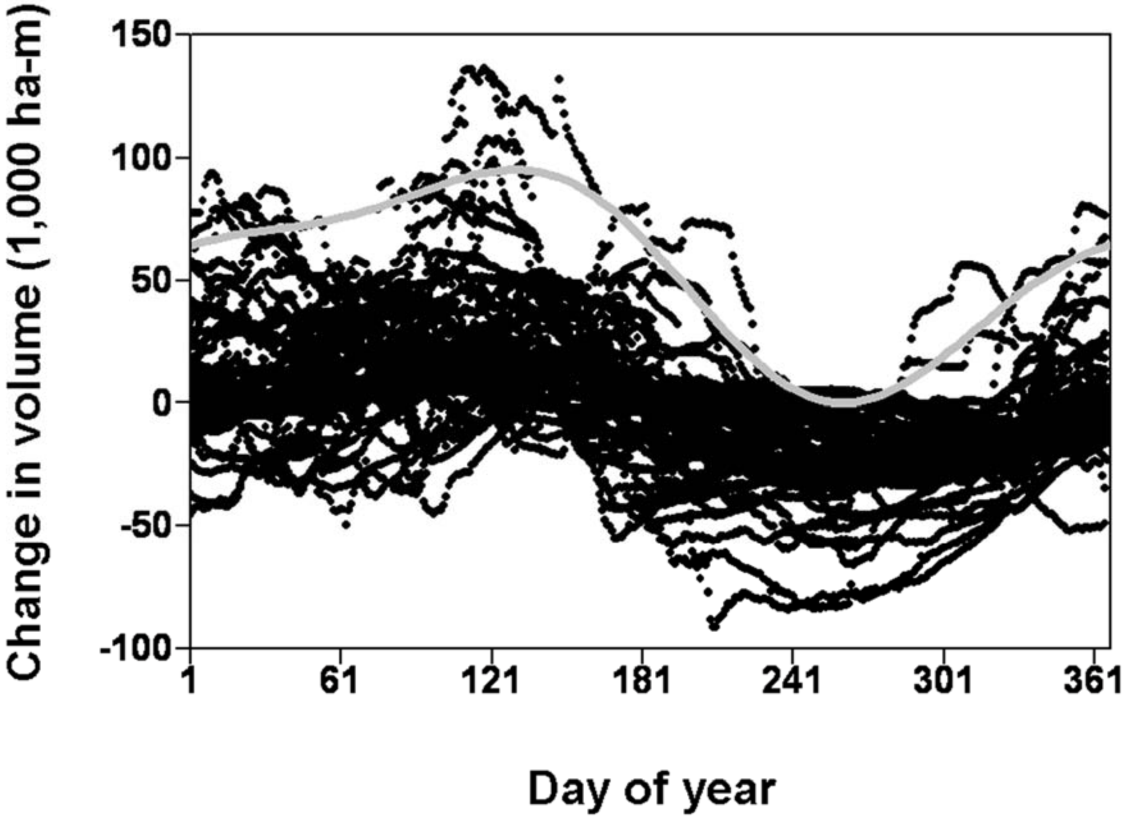

Figure 3.2 97.5 quantile model fit to the distribution of 60 day summed changes in water volume.

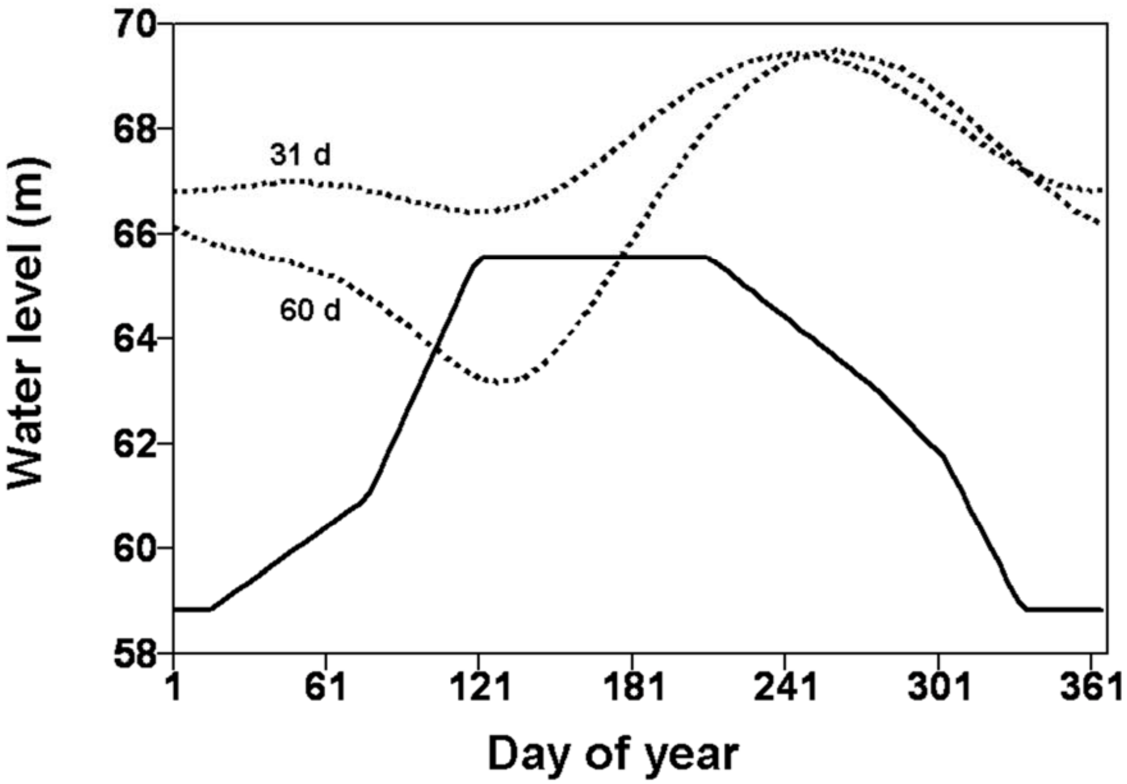

Figure 3.3 Generated guidelines for the 31 and 60 day sum periods using the 97.5 quantile compared against the current rule curve.

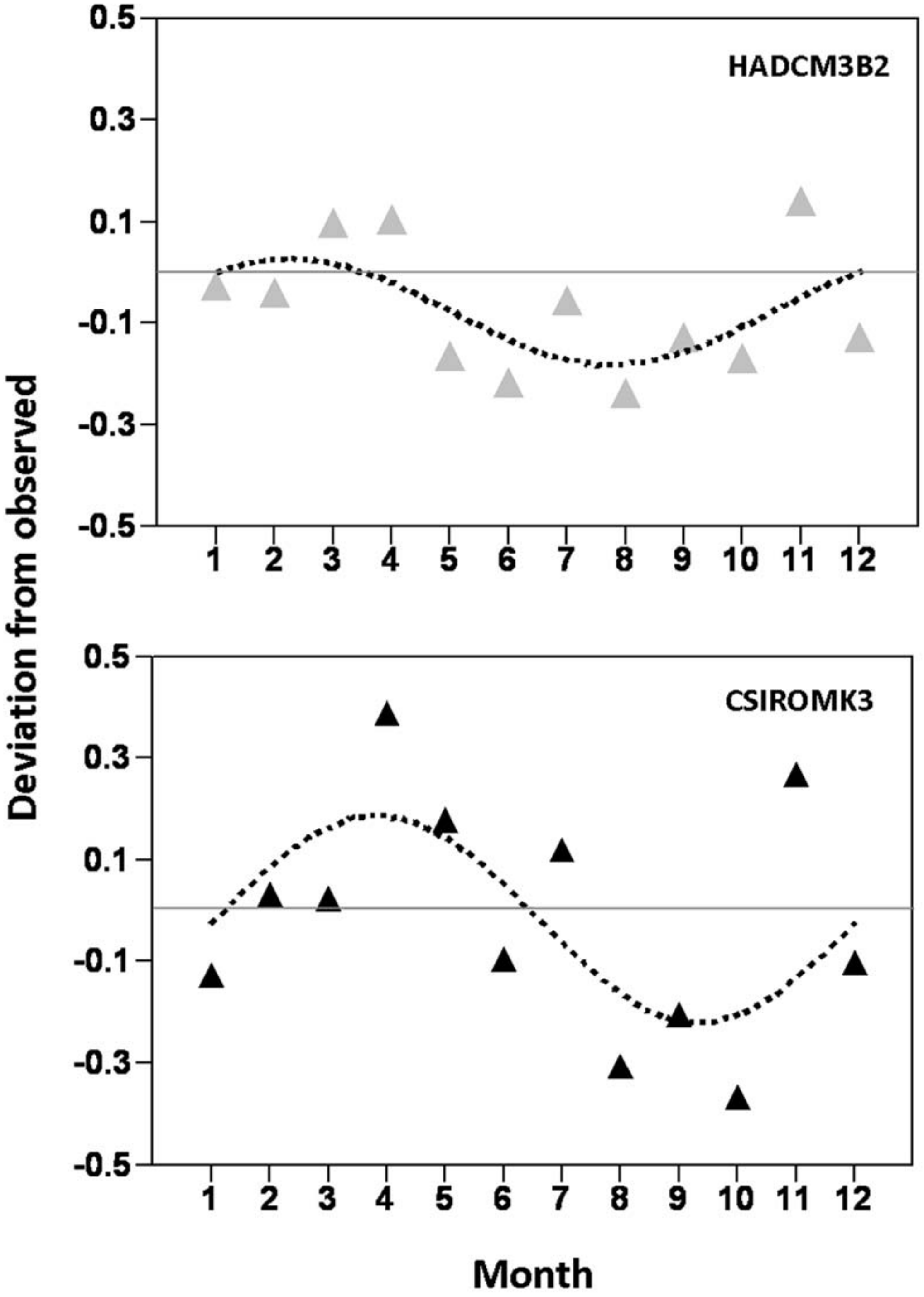

Figure 3.4 Deviation of predicted precipitation from 30 year average precipitation.

0 represents baseline average precipitation and predictions range from small deviations to a twofold increase in precipitation.

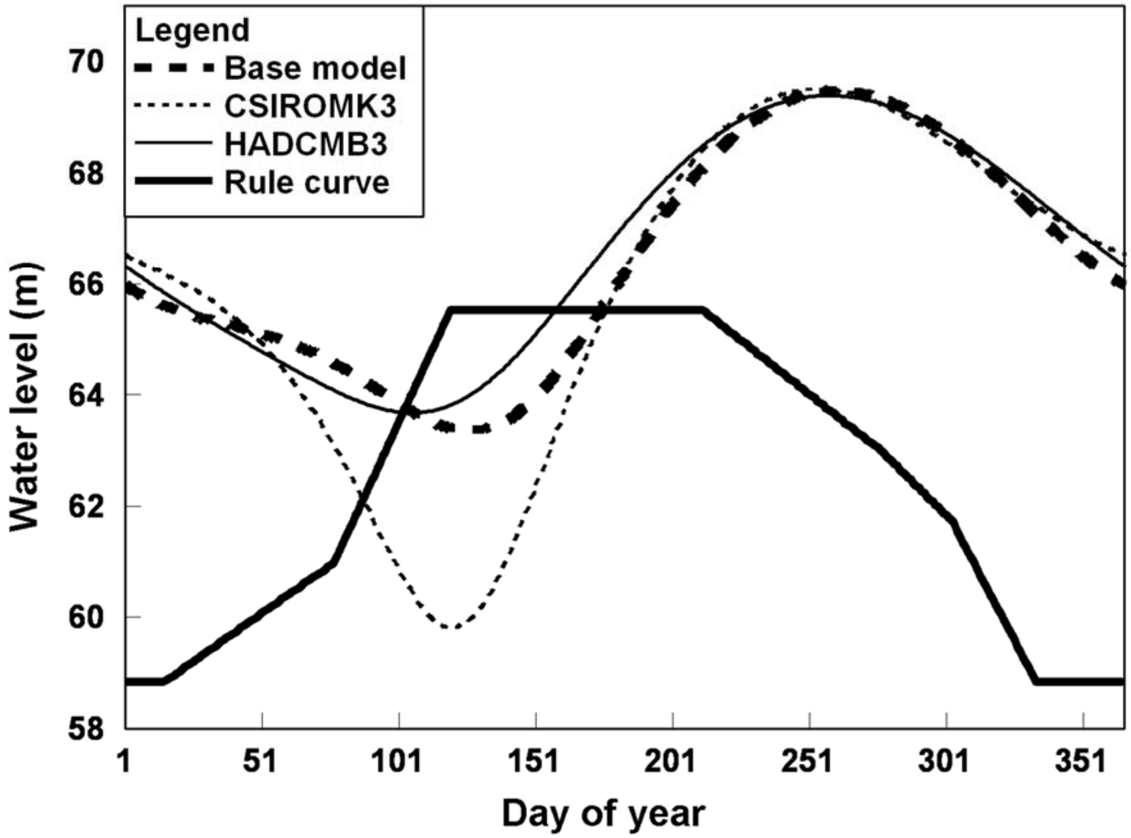

Figure 3.5 Generated guidelines for the climate models using a 97.5 quantile and 60 day sum period

The lines are compared to the current rule curve and the 97.5th quantile, 60 day base model.

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CHAPTER IV

VEGETATION DYNAMICS IN FLOOD CONTROL RESERVOIRS: A REMOTE SENSING APPROACH

Introduction

Wetland areas are extremely diverse and complex ecological systems that sustain a wide variety of organisms ranging from completely obligatory to facultative species (Cronk and Fennesey 2005; Mitsch and Gosselink 2007). The impact of wetland habitats on waterfowl cannot be understated, its impact on fish populations is significant, and many mammal species are supported by wetland ecosystems (Tiner 1984; Mitsch and Gosselink 2007). Large reservoirs often have wetland areas located at the tributary mouths that are seasonally connected to the reservoir depending on water level. These areas often have herbaceous or moist soil vegetation communities that reflect those in the original river floodplain, and can provide potential structure and food for some fish populations and migratory birds (Junk et al. 1989; Gido et al. 2002; Miranda et al. 2013 Strader and Stinson 2005). Flooding in these areas is strongly influenced by water levels within the reservoir, with fluctuations periodically connecting or isolating the floodplain. Flood control reservoirs in particular, often have drastic fluctuations where water is held in the reservoir to attenuate flood events during the wet season and released during the dry season. Timing, depth, and duration of these fluctuations can be significant disturbances to vegetation (Casanova and Brock 2000), both in the floodplain and in the arms of the reservoir (coves), and can drive amount as well as temporal and spatial distribution of wetland vegetation (Junk et al. 1989; Ahn et al. 2004). Exposed sites provide opportunity for wetland herbaceous plants to germinate (Low and Bellrose 1944, Fredrickson and Taylor 1982).

Habitat complexity associated with vegetation has been linked to more diverse and abundant fish communities through food-webs, spawning and rearing habitat, and predator prey interactions (Bryan and Scarnecchia 1992; Dibble et al. 1997; Petry et al. 2003). Vegetation can have an especially large effect on juvenile game fish (Dibble and Harrel 1997; Snickars et al 2004; Dagel and Miranda 2012). Flood control reservoirs are often not managed for the wetland resources they contain because the primary concern is about downstream flows, not processes that occur in transitional zones at the entrance to reservoirs. Water level fluctuations in general have been suggested to contribute to the instability and cyclical behavior of many reservoir fish populations (Beam 1983; Sammons and Bettoli 2000; Allen and Miranda 2001). It is probable that given the importance of vegetation to aquatic ecosystems, vegetation abundance that is influenced by water level fluctuations can generate or exacerbate the cyclical nature of fish communities.

Despite the importance of vegetation in reservoirs, there is little information about the effect water levels have on wetland and terrestrial vegetation specific to the operation of large flood control reservoirs by the USACE, Plausibly, lack of such information can be attributed to the difficulties associated with conducting vegetation surveys in often remote areas with limited access by watercraft due to low water levels, or access by land vehicles due to hydric and edaphic conditions. I used a remote sensing method to assess vegetative abundance in dewatered areas of reservoirs. Specifically, my objective was to describe the relationship between water level regime and density of wetland and terrestrial vegetation in dewatered areas. I compared vegetation abundance over a large temporal and spatial scale at a reservoir in Northwest Mississippi, and investigated relationships between water level regime and vegetation coverage.

Methods

Study Site

The study was conducted in Enid Reservoir, Yalobusha County, Mississippi. This reservoir is a flood-control reservoir built in the late 1940's and has a mandated fluctuation between summer pool and winter pool of 6 m. The reservoir was built as part of a comprehensive flood plan to protect the Yazoo River Basin from extreme flooding. Vegetation differs between coves in the reservoir and the floodplain of the principal tributary, the Yocona River. The difference in vegetation is primarily related to site-specific seed banks, edaphic conditions, and propagule sources of vegetation. The floodplain represents bottomlands and accumulation of alluvial soils with well-established wetland seed banks. Coves represent the inlets of minor tributaries and include primarily areas previously occupied by terrestrial upland vegetation. Additionally, the slope of coves is generally steeper than those of the floodplain. The areas chosen for analysis measured approximately 225 ha. The areas were located in areas that experience annual dewatering and flooding and were being used in ongoing fish recruitment studies.

Data collection and processing

I used satellite data from the NASA's Earth Observing Satellite, Landsat 5 TM. This is a multi-spectral, moderate-resolution satellite providing free imagery every 16 d. Landsat images have been popular for land cover analysis because of their large field of view and resolution of 30 m.

Numerous vegetation indices are popular for vegetation analyses. Most indices rely on the spectral reflectance properties of the red and infrared region of the electromagnetic spectrum. Some vegetation indices can be calculated by separating major components of the satellite image, much like a principal component analysis. One of the most powerful transformations is the Tasseled Cap Transformation (TCT)(Crist and Cicone 1984; Crist and Kauth 1986). This transformation separates components that reflect vegetation characteristics and rotates the data along orthogonal axes known to correlate with specific vegetation characteristics. The rotation separates spectral signatures to emphasize three distinct components of vegetation: brightness, greenness, and wetness (Crist and Cicone 1984; Crist and Kauth 1986). The greenness component is typically used as a measure of the coverage and relative abundance of green vegetation present in an image (Crist et al. 1986).

I downloaded data from the USGS Global Visualization website, http://glovis.usgs.gov. Scenes recorded in 1987-2009 were used, excluding 8 years when data could not be collected because of cloud cover. I used scenes taken in late September or early October to standardize time of data collection and to capture the maximum variation in plant vigor among years. The growing season for most vegetation typically ranges between time the water level of the reservoir is drawn down and time of the first freeze, usually in late November. Images in September-October provided a snapshot of plant growth before senescence begins in late October-November. All images were acquired within 16 d of each other. This provided a 14-year data set where changes in relative amount of green vegetation could be analyzed. Images were subset to the area surrounding Enid Reservoir in Northern Mississippi, and the TCT transformation was applied using ERDAS Imagine software version 10.0 (ERDAS Inc 2010). Polygons were created for the floodplain and cove sites in the area where water levels fluctuate and mean greenness was calculated for each polygon in each year at each site using ArcGIS version 10 (Environmental Systems Research Institute 2010). The resulting transformations and floodplain polygon are provided in Figure 4.1.

I used analysis of covariance to model mean greenness index relative to days of exposure (i.e., not covered by water, dewatered) and precipitation. Precipitation was included to account for variability in the greenness index potentially attributed to annual differences in moisture availability during the fall drawdown period. Precipitation data were obtained from the PRISM climate group (Oregon State University, Corvallis) for August and September and summed into one variable. Exposure and precipitation were considered covariates and habitat type defined as cove or floodplain was the class variable (GLM procedure; SAS institute 2012). Preliminary scatter plots suggested that relationship between the greenness index and exposed days was non-linear. Thus, a natural log transformation was applied to number of exposed days to linearize for application of linear regression. I used Cook's distance, which measures the individual influence each data point has on the regression relation, to evaluate the fit of the models (SAS Institute 2012). Exposure was quantified with three different linear models.

In model 1, I used the log-transformed total number of frost-free days where the area was exposed within one year (Figure 4.2, exposure 1 + exposure 2 added), precipitation in August and September, and the habitat type as a categorical variable. This model investigates the general relationship between vegetation abundance, total growing season, precipitation during the growing season and location in the reservoir. In model 2, I considered the log-transformed number of frost-free days the water was below the level at which the floodplain is inundated (75 m) in the spring and the fall (Figure 4.2, exposure 1 and exposure 2) as separate variables. Days exposed in the spring included exposure in winter and spring before water level was brought up to normal pool, and fall exposed days were late-summer and fall after water level was drawn down (Figure 4.2). This model investigated the possibility of vegetation persisting through flood events by separating the growing season into spring and fall growing seasons disconnected by the summer high water level. If the spring growing season (exposure 1) contributed significantly to the model, this would suggest that some aquatic vegetation may persist through high water events and affect mean greenness values in the fall. In model 3, I considered the log-transformed number of frost-free days exposed since the last flooding event (exposure 3), which could have occurred in the same year or in a previous year (Figure 4.2).

In 2007, there was no distinction between fall and spring growth periods because the water level was never higher than 75 m. Thus, 2007 was not included in the analysis for model 2. If draw-down time for year i was larger than 1 year, models 1 or 2 did not include year i. Draw-down time was greater than 1 year in 2007 only. Relationships among variables were classified as strong ($P \leq 0.05$), weak ($0.05 < P \leq 0.20$), or lacking ($P > 0.20$).

In fall of 2011 and 2012, I also conducted onsite surveys to identify plant assemblage composition and measure plant height and relative density in the floodplain area of Enid Reservoir. Plants were identified to genus for the family Poaceae, and to species for all others following Schummer et al. (2012), Cronquist (1980), and Godfrey and Wooten (1979). I haphazardly established two adjacent 400 m transects in the backwater sampling area which bisected the entire area. I measured plant height and relative density using a modified cover board (Nudds 1977) at approximately 15-m intervals along each transect (Anderson 1942; Burnham et al. 1980; Krebs 1989). The modified cover board had alternating black and white 1 in^2 squares along the width and length of the board. Plant height was measured as the tallest plant showing on the board and a density index was constructed as number of squares covered by vegetation divided by total number of squares available to be covered (Robel et al. 1970; DeVos and Mosby 1971; Nudds 1977; Hays et al. 1981). The index ranged from 0 to 1 and reflected the fraction of squares including vegetation. Measurements were taken over several fall months in 2011 and 2012 in the floodplain, and once in fall 2012 in the cove habitat. Three transects in the cove were established sequentially from the front to the back of the cove to determine if there were any longitudinal gradients present in plant height and density (Oosterhorn and Kapelle 2000; Nash et al. 1999). Plant height and density for the floodplain and cove habitats were compared using analysis of variance (GLM procedure; SAS institute, 2012).

The wetland indicator status and minimum frost-free days obtained from www.plants.usda.gov were used as assembly rules to predict the vegetation composition relative to changing water levels. Wetland indicator status denotes occurrence probability of a species in wetlands. Obligate wetland species (OBL) occur exclusively in wetland areas. Facultative wetland species (FACW) are usually found in wetlands, but have the ability to tolerate non-wetland conditions. Facultative species (FAC) occur equally in wetland and upland habitats. Facultative upland species (FACU) are usually found in upland habitats, but occasionally in wetland areas. Upland species (U) are found exclusively in upland areas (Reed 1982; Lichvar et al. 2012). Obligate wetland species have reduced ability to survive an extended drawdown event, where upland species have reduced ability to survive prolonged flooding events. Facultative species will have some ability to tolerate flooded or drawn down conditions (Cronk and Fennessey 2005; Mitsch and Gosselink 2007).

Results

Model 1, which combined exposure 1 and exposure 2, precipitation, and habitat type was significant overall (F=12.0, P<0.01). Precipitation contributed weakly to the model (P = 0.07). The correlation between precipitation and mean greenness had a negative relationship to the greenness index (r = -0.46). Cook's distance revealed that one year was contributing greatly to this relationship. Removal of this year reduced the contribution of precipitation to the model (P increased to 0.26). Habitat type and interaction between habitat and growing season did not influence mean greenness (P > 0.2) meaning that floodplain and cove sites responded equally to water level fluctuations.

Based on these analyses, I removed precipitation and habitat type from subsequent models.

Model 2 considered the relationship between greenness and exposure 1 and exposure 2 separately. This model was statistically significant overall (F = 27.1, P < 0.01) and explained 71% of the variation in mean greenness values. Exposure 1, however, did not contribute significantly to the model (P > 0.2). This lack of significance indicates that a longer growing season in the spring does not affect amount of green vegetation in the following fall. Any growth achieved in spring may not persist past flooding events to be of use to fish and wildlife in subsequent drawdowns.

In model 3 I investigated influence of the fall growing season further by modeling only exposure 3. The model was statistically significant (F = 73.2, P < 0.01) and explained the most amount of variation ($r^2 = 0.75$) in mean greenness values of all three models. This model points to the importance of the growing season after a drawdown for generating vegetation for fish and wildlife.

On site surveys in the floodplain area revealed strong differences in plant height between 2011 and 2012 (t = 27.9, P < 0.01; Figure 4.3). Plant height averaged 8 cm (SE = 0.40) in 2011 and 46 cm (SE = 0.35) in 2012. However, plant height measurements were as high as 51 cm in 2011 and 104 cm in 2012. Differences in plant density were also strong between years (t = 8.4, P < 0.01; Figure 4.4). The plant density index in 2011 was 0.69 (SE = 0.015) and 0.93 (SE = 0.013) in 2012. A greater index indicates a greater density.

Plant communities varied between floodplain and cove sites. Vegetation in the floodplain site contained a mix between obligate wetland species and facultative species

(Table 1). In contrast, cove sites had fewer species and had only facultative species and some upland species. The floodplain sites were dominated by a mixture of *Panicum* spp., *Polygonum* spp., and various sedges (Cyperaceae) and rushes (Juncaceae), all of which are obligate wetland or facultative wetland species. The cove sites were dominated by a mix of *Sesbania* and *Eupatorium* spp. No obligate wetland species were detected in coves. Vegetation in cove sites showed a distinct longitudinal pattern with height increasing toward back of the cove where exposure time was longer ($P < 0.01$) (Figure 4.5). Plant density between transects showed a strong longitudinal gradient with a less dense vegetation in front of coves where exposure time was brief ($P < 0.01$). Mean density index was 0.67 in the front of the cove, 0.83 in the middle, and 0.97 in the rear of the cove ($SE = 0.03$).

Discussion

The relationship between vegetation relative abundance (as indicated by the greenness index) and number of growing days since last flooding event was logarithmic. The least abundant vegetation occurred when the growing season was shortest. However, greatest greenness values occurred when the growing season, which began prior to image acquisition, was approximately 20-35 days. This curvilinear relationship may be attributed to two factors, plant competition and sensor inefficiency. Plant communities often display density-dependent patterns and different plant densities can either facilitate or inhibit further plant growth (Callaway and Walker 1997; Goldberg et al. 2001). Competitive interactions are often dictated by general environmental factors such as light availability, and site-specific factors such as flooding and precipitation (Smith and Huston 1990; Holmgren et al. 1997), which in a flood-control reservoir can have a wide range. Alternatively, inability of remote sensing platforms to calculate an increase in leaf-area could contribute substantially in this relationship. The Normalized Difference Index has been documented to saturate and lose ability to sense increased photosynthetic activity at high levels of plant abundance, and this phenomenon may be in effect with the TCT. Most attempts to correlate leaf area with satellite image are in their infancy (Zheng and Moskal 2009). Utility of a plant senescence index could be investigated in future research with reservoir vegetation (Merzlyak et al. 1999). The launch of Landsat 8 in February 2013 will allow correlation of onsite measurements with concurrent satellite data collected in the future and could further potential knowledge about the utility of the TCT.

In light of the results from the remote sensing analysis the drastic differences between floodplain onsite height and density measurements in 2011 versus 2012 may be explained by a longer growing season in 2012. Water levels never exceeded 75 m in 2012 and provided an exposure period of approximately 1 year. Conversely, 2011 was a normal year where water levels did not fall below 75 m until mid September, providing a shorter exposure period compared with 2012. The longitudinal gradient for height in the cove could also be explained by flood frequency and duration (Maltchik et al. 2007). With the extended growing season in 2012, areas close to the front of the cove that were submerged longer had less dense and shorter vegetation than areas in the back of the cove that were exposed longer. A more frequent and longer inundation can inhibit direct growth of vegetation, but also development of a viable seed bank closer to the mouth of the cove (Casanova and Brock 2002). The back of the cove in contrast is flooded less frequently and for a shorter duration, which provides a longer growing season and the potential to develop a seed bank.

Calculating zonal statistics on an area affected by water level fluctuations resulted in water comprising most of the images in some years. Water reflects very dark in the greenness band of the TCT, and this would mask any vegetation present under the water. The TCT would discount any vegetation present when in reality there may be vegetation underneath the water. Through a review of available literature, I assumed that the years with high water levels inhibited further plant growth underneath the water and eliminated most plants present (Frankland et al. 1987; van der Valk 1981; Casanova and Brock 2002). Fraser and Kamezis (2005) and Smith et al. (2002) reported reduced germination and survivorship among many obligate wetland species under extended flooded conditions. Any wetland or moist-soil plants which were specifically adapted to persist in extended flooded conditions discounted in this treatment of the data were not abundant enough to contribute significantly to mean greenness in fall as evidenced by model 2. This could be because wetland plants lack the structural integrity and metabolic pathways to persist in non-inundated environments. Aquatic adapted plants will dessicate in drawn down conditions and be generally unavailable to fish and wildlife use after an extended drawdown period. Thus, discounting vegetation that may be present under flooded conditions was valid in my case.

It is clear from satellite images and on-site surveys that a longer growing season results in greater vegetation development. The fact that growing days available in spring did not contribute significantly to the model indicates that timing of fall drawdown may be of primary importance to vegetation in flood control reservoirs and is consistent with results of other studies (Bellrose et al. 1983; Wlosinski et al. 2000; Ahn et al. 2004). This can have implications beyond simple vegetation abundance. Dagel and Miranda (2012) reported a lesser catch of age-0 crappie in spring when higher water levels had been maintained the previous fall. They suggested that higher water levels in the previous fall could impact littoral vegetation. The results reported in this chapter support that suggestion. Higher water levels maintained in fall can result in lesser vegetation abundance the following spring, producing conditions not conducive to age-0 crappies through decreased predator avoidance and a less diverse food web. These interactions among vegetation abundance, water level fluctuations, and juvenile fish success could contribute to the variation among crappie year classes (Dagel and Miranda 2012).

This analysis points to timing of fall drawdown rather than allowing growing time in spring as being the most important target for increasing vegetation abundance. Efforts to increase time available in fall will decrease abundance of obligate wetland plants. Most obligate wetland plants depend on some amount of standing water for metabolism, reproduction and dispersal (Cronk and Fennesey 2005). An earlier drawdown date will shift the plant community away from obligate wetland species, towards a facultative, tolerant community (Kadlec 1962; Casanova and Brock 2012,Table 1). Duration of growing season is likely only one small part of the overall effect of water levels. Many factors contribute to determine plant community composition (Gleason 1927; Van Der Valk 1981). It is likely that nutrient availability, previous plant distributions, competition, substrate, turbidity, and plant type (e.g. perennial/annual, vernal/autumnal) to name a few all play an important role in structuring these communities (Kadlec 1962; van der Valk

1981; Van Geest 2005). More research is needed to determine what effect of various drawdown scenarios would be in flood control reservoirs.

Any management action needs to consider the desired plant community and if the action will provide the effect desired. In the case of enhancing spawning and nursery habitat in Enid Reservoir, an earlier drawdown time in fall will result in a greater abundance of emergent species (Kadlec1962) which will survive desiccation and senescence to be available in the following spawning/nesting season (Van Geest 2005).

Flood control reservoirs have a congressionally mandated role in mitigating damage to downstream assets. Improving fish habitat does not necessarily need to interfere with this goal. An earlier drawdown time will have a low impact on downstream interests, but could have a large impact on fish and wildlife habitat. However, many competing users (e.g., recreationalists) would oppose such a drawdown. Future research is needed to validate these results with ground observations and to investigate plant growth beyond what satellites are able to measure. It is also unknown if age-0 fish that have hatched and developed in these vegetated habitats continue to use these habitats later in the season. If they do, early drawdown may have detrimental effects on age-0 fish that use these habitats in fall that are concentrated by reduced water levels.

Table 4.1 Species list of plant communities in the floodplain and cove of Enid Reservoir[1].

Common name	Scientific name	Floodplain	Cove	Wetland indicator status	Early drawdown effect
Aster	*Symphyotrichum* spp.	✓	✓		
Broomsedge	*Andropogon* spp.	✓	×		
Mosquitofern	*Azolla caroliniana*	✓	×	OBL	-
Beggarticks	*Bidens aristosa*	✓	✓	FACW	+
Yellowfruit sedge	*Carex annectens*	✓	×	FACW	+
Shallow sedge	*Carex lurida*	✓	×	OBL	-
Buttonbush	*Cephalanthus occidentalus*	✓	×	OBL	-
Spotted sandmat	*Chamaesyce maculata*	✓	✓	FACU	+
Redroot flatsedge	*Cyperus erythrorhizos*	✓	×	OBL	-
Chufa	*Cyperus esculentus*	✓	×	FAC	+
Barnyard grass	*Echinochloa crus-galli*	✓	×	FACW	+
Barnyard grass	*Echinochloa muricata*	✓	✓	FAC	+
Creeping burhead	*Echinodorus cordifolius*	✓	×	OBL	-
Spike rush	*Eleocharis obtuse*	✓	×	OBL	-
Lovegrass	*Erlagrostis* spp.	✓	×		
Dogfennel	*Eupatorium capillifolium*	✓	✓	FACU	+
Boneset	*Eupatorium serotinum*	✓	×	FAC	+
Sumpweed	*Iva annua*	✓	×	FAC	+
Common rush	*Juncus effuses*	✓	×	FACW	+
Japanese clover	*Kummerrowia striata*	✓	×	FACU	+
Cutgrasses	*Leersia* spp.	✓	×		
Sprangletop	*Leptochloa* spp.	✓	×		
Seedbox	*Ludwigia alternifolia*	✓	×	OBL	-
Panic grass	*Panicum* spp.	✓	×		
Denseflower Knotweed	*Polygonum glabrum*	✓	×	OBL	-
Pennsylvania smartweed	*Polygonum pensylvanicum*	✓	✓	FACW	+

Table 4.1 (Continued)

Marsh smartweed	*Polygonum hydropiper*	✓	✗	OBL	-
Curly dock	*Rumex crispus*	✓	✗	FAC	+
Table 4.1 (continued)					
Giant arrowhead	*Sagittaria montevidensis*	✓	✗	OBL	-
Bald cypress	*Taxodium distichum*	✓	✗	OBL	-
Round sedge	*Cyperus echinatus*	✗	✓	FAC	+
Cocklebur	*Xanthium strumarium*	✓	✓	FAC	+
Fragrant flatsedge	*Cyperus odoratus*	✗	✓	FACW	+
Common rush	*Juncus effuses*	✗	✓	FACW	+
Whiteroot rush	*Juncus brachycarpus*	✗	✓	FACW	+
Coffeeweed	*Sesbania herbacea*	✗	✓	FACW	+
Broadleaf signalgrass	*Urochloa platyphylla*	✗	✓	FAC	+

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[1] Wetland indicator status acronyms: OBL=Obligate wetland, FACW=Facultative wetland, FAC=Facultative FACU=Facultative upland. Species only identified to genus were not assigned a wetland indicator status and have no early drawdown effects listed.

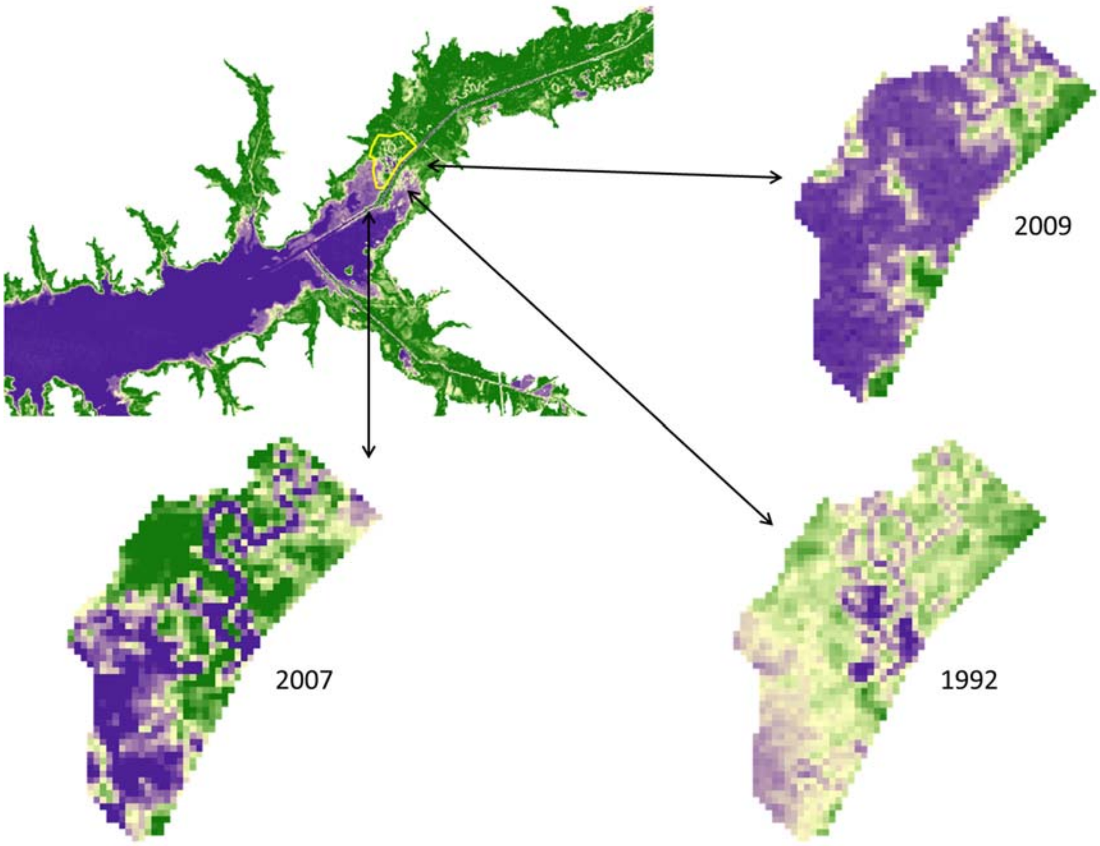

Figure 4.1 Tasseled Cap Transformations for a floodplain site in Enid Reservoir

Images were taken in late Sep or early Oct. Green represents vegetation and blue represents water. The yellow polygon indicates the area used to index the mean greenness for the image. The 2007 image had the longest growing season, 1992 had an intermediate growing season, and 2009 had no growing season.

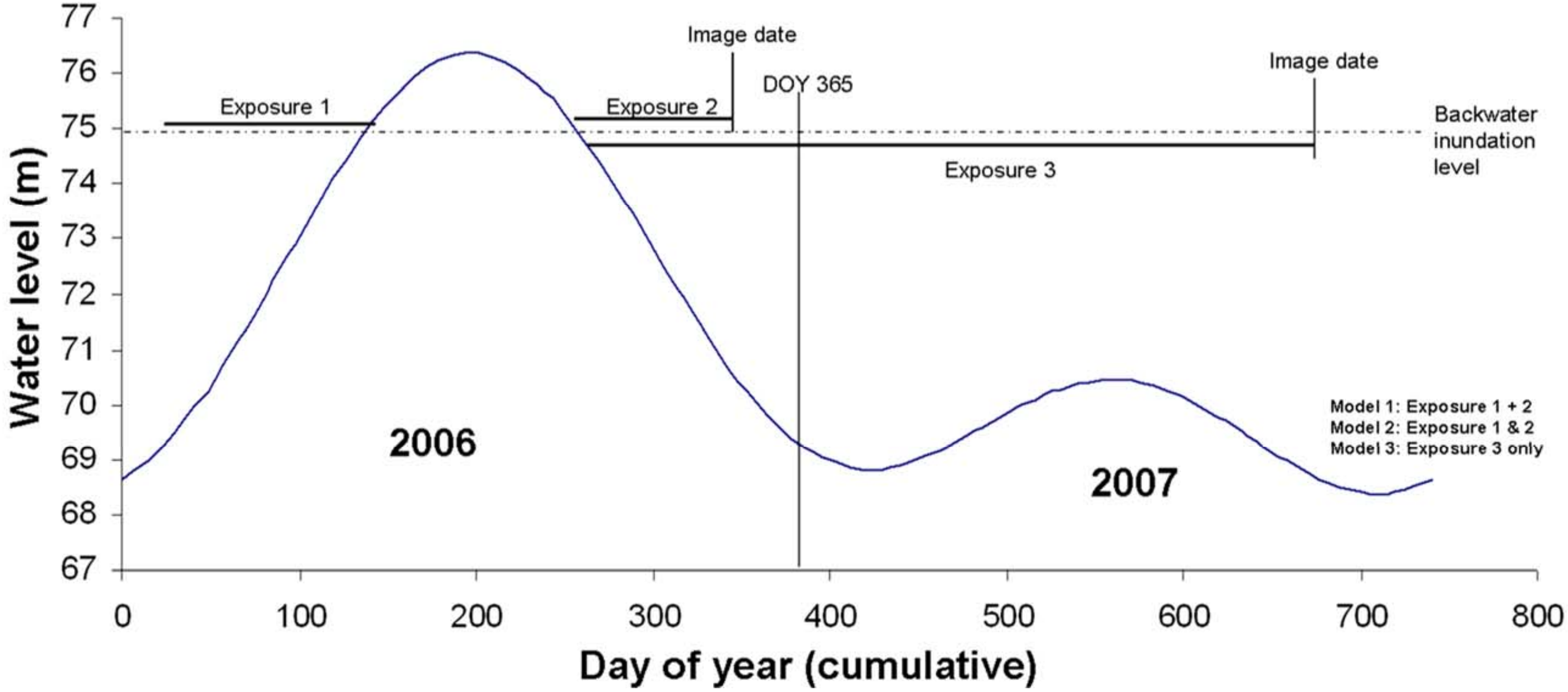

Figure 4.2 . Depiction of exposure periods considered in three models.

Model 1 investigates the effect of the total growing season in one year. Model 2 investigates growing seasons separated by high water events. Model 3 investigates the growing season since last high-water event. In years when the floodplain was inundated, exposure 3 is the same as exposure 2. In years where the growing season consisted of greater than one year, exposure 3 accounted for the longer growing season. A vertical reference line at DOY 365 is provided to illustrate the extended growing season in 2007. The horizontal dashed reference line represents the point at which the floodplain becomes inundated.

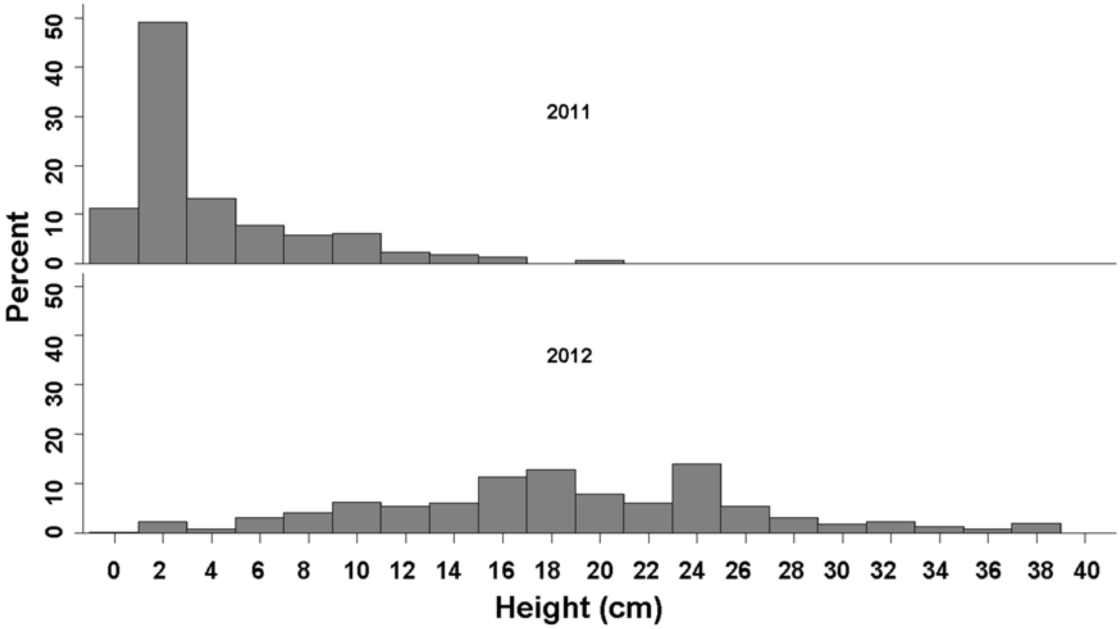

Figure 4.3 Percentage plant height frequency distribution in the floodplain.

The x axis is plant height measured in centimeters. The top panel depicts plant height distribution present in 2011, and the bottom represents 2012.

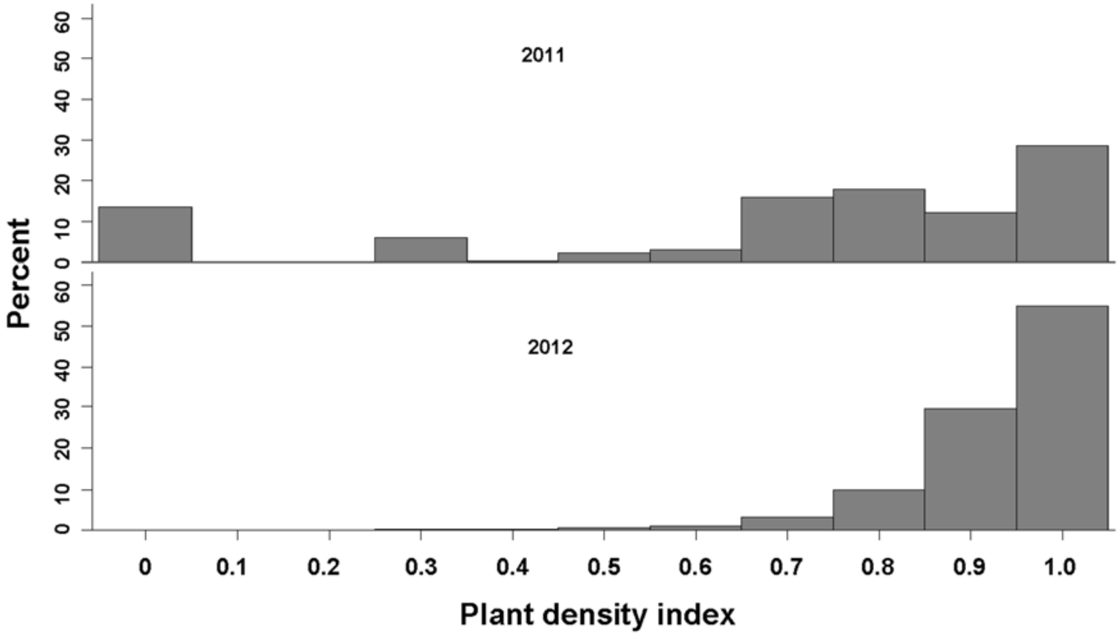

Figure 4.4 Floodplain plant density index distribution (%) in 2011 and 2012.

Density was calculated from a modified cover board as number of 1-in squares covered by vegetation divided by total number of squares available to be covered. The x axis indicates plant density index with 1 being the most dense. The top panel depicts plant density distribution for 2011 and the bottom panel depicts 2012.

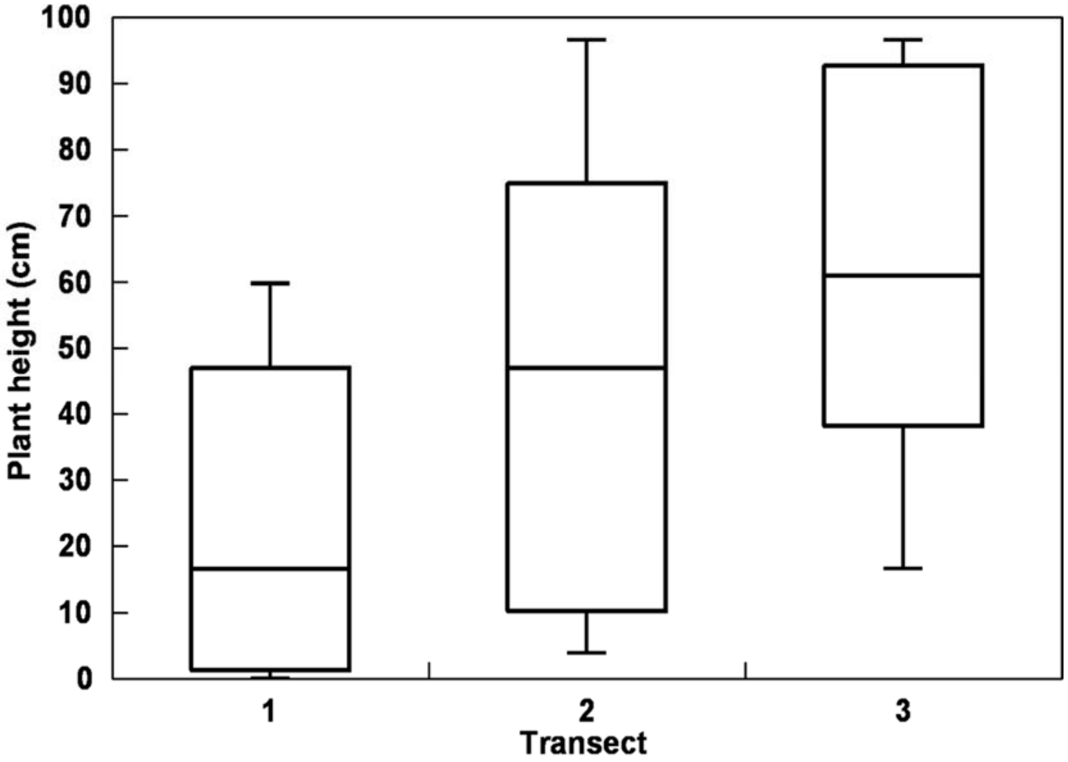

Figure 4.5 . Plant height relative to position in the cove

Transect 1 was located near the mouth of the cove, transect 2 was located halfway between the mouth and the back of the cove and transect 3 was located at the back of the cove. The whiskers represent the minimum and maximum values, the box represents the inter-quartile range and the horizontal line represents the median value for each transect.

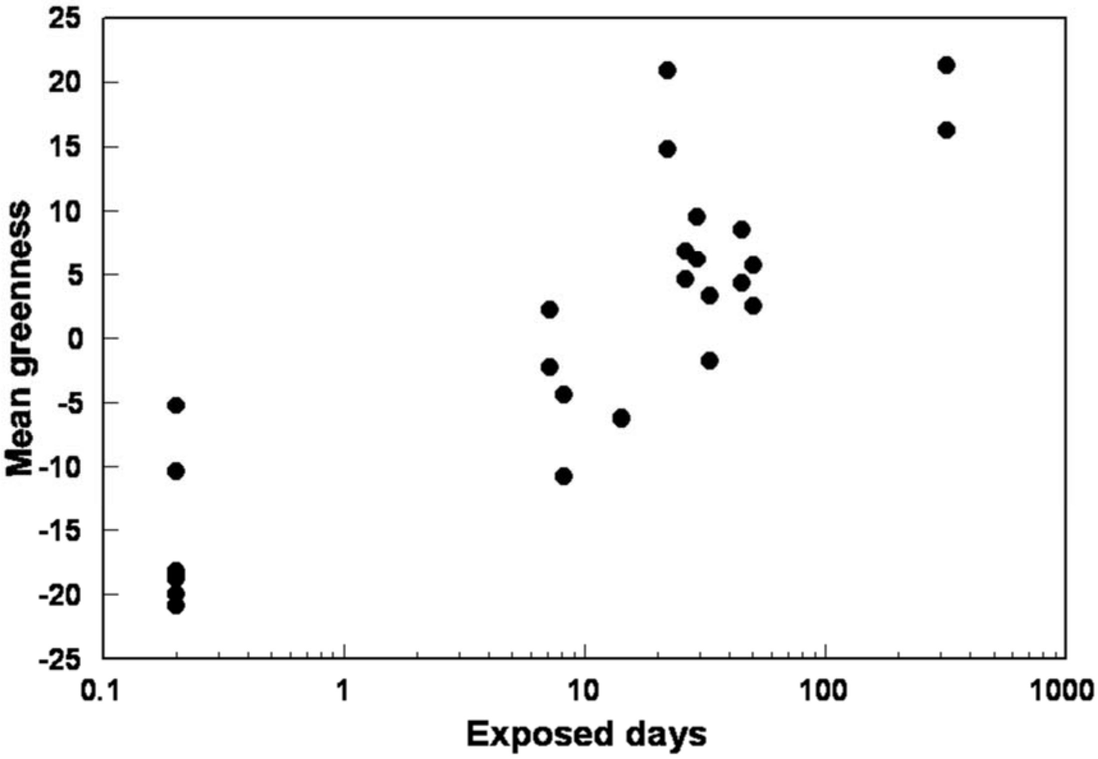

Figure 4.6 Mean greenness plotted against total number of exposed days since last flood event.

The relationship is logarithmic suggesting plant competition, sensor inefficiencies, or both.

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CHAPTER V

SYNTHESIS AND FUTURE RESEARCH

Habitat management is an essential part of managing fish and wildlife populations in altered systems. Habitat is the basis for the success or failure of a species and is often the focus of efforts to improve populations for greater recreational value. There is a vast amount of literature detailing interagency and multiuser strategies for enhancing habitat in mixed-use areas. Flood control reservoirs represent some of the most complex multi-use areas. I use the phrase multi-use instead of multi-purpose because flood control reservoirs often have only one primary purpose, whereas they serve many uses. People using and benefiting from large reservoirs range from landowners downstream, electricity consumers many miles away, recreational and subsistence fishers, and water-sport recreationists. The economic spectrum occupied by this range of users is equally diverse. With this diversity of users comes natural conflict about how reservoir water levels are to be managed and these interests are not always wholly compatible. Fish and wildlife managers are often tasked with managing and improving populations in these reservoir environments. What is good for fish populations may not be ideal for waterfowl management, and neither of these goals may optimize flood control for people downstream. However, opportunities for integration of these goals may exist with increased information on assessment of modifications in reservoir management. This thesis provides tools in a reservoir management toolbox for the natural resource manager. An understanding of the procedures involved for changing rule curves is basic for suggesting a change in operations. Chapter two provides a detailed explanation of this process. I uncovered three possible legal foundations for changing rule curves, each with a different scope. Selecting a method to request a change in operations will depend on how much the change will affect the significant purpose, which in flood control reservoirs is flood control. Thus, managers contemplating a change to rule curves will need to have an understanding of how the change might impact flood risk.

Determining flood risk resulting from a change in operation is often a complicated process requiring specialized data and complicated software. Most managers do not have the time or the expertise to quantify flood risk. Requests for changes to rule curves can consequently be unrealistic with respect to the risk of flooding downstream. Chapter three provides a simple method for quantifying and visualizing the flood risk of a contemplated action. A computer program provided in an appendix features a user-specified flood risk, visual graphics, and is statistically based on past flood history. The utility of this method will be to allow more educated requests on the part of managers. Improved communication between reservoir operators and natural resource managers will occur as a result of managers being better educated on the risk of flooding downstream. A method for estimating risk of an action is crucial for successfully suggesting any management change in a flood control reservoir.

A sound ecological basis is also required for any management action requested. To facilitate understanding habitat dynamics in flood control reservoirs I investigated the relationship between water level changes and vegetation abundance in reservoirs. Vegetation drives many population-level processes in aquatic/wetland systems, and this type of analysis can provide management recommendations for fish and wildlife populations in reservoirs. I found vegetation to be strongly influenced by timing of drawdown. Earlier drawdown periods will allow for an increased growing season for moist soil vegetation. After flooding, this vegetation can in turn be available to fish spawning in the subsequent spring season. Waterfowl could also benefit from an earlier drawdown date, as it would provide conditions needed to develop high-quality food. This food would only be of use if the water levels were raised again in winter and spring to levels that allowed access to the area.

Feasibility of many scenarios could be assessed by the methods I provide. One important variable driving waterfowl use is the forage quality of plants present and access provided by water levels. Typically, water levels are drawn down in summer to provide a long growing season for forage plants in the area (Twedt et al. 1998; Taft et al. 2002). As plants senesce and waterfowl immigrate, water is raised to provide access to high-quality forage in winter. The process of changing the current rule curve as well as the flood-risk feasibility of such changes can be assessed with the methods I provide. I also provide information on effect of water level management on plants present in the Yazoo headwater reservoirs to augment management decisions in this area, and in the region.

Feasibility of changing rule curves to benefit fish populations can also be assessed with the methods I provide. Facilitating access to floodplain spawning areas for floodplain oriented fish is important for fish in flood-control reservoirs (Dagel and Miranda 2012). A rule curve which allows a higher water level earlier in spring, and lowers water levels earlier in fall will allow development of vegetation and allow access to the vegetation by spawning and age-0 fish could improve populations in many reservoirs (Miranda et al. 2011). Feasibility and impact of this scenario can be assessed with information provided in chapters two and three. Chapter one provides a guide for actually requesting and communicating with reservoir operating personnel.

Cooperative efforts with various management agencies to combine existing but unpublished databases on plant communities in these reservoirs could be of great utility to furthering understanding of the vegetation dynamics. One of the failings of this study was its lack of replication and limited scope. Field surveys in the future could focus on quantifying plant species diversity and species richness during vernal and autumnal growing periods. A quantification of the available seed bank in different areas could improve knowledge of what the potential plant community could be in different places and under different management scenarios. A qualitative modeling approach could then answer in more detail questions of when, how much and how fast drawdowns should occur.

This thesis is not intended to justify of a change in a rule curve. It is intended rather as a framework and guide for developing situation-specific requests to reservoir management agencies. Many of the methods presented are applicable and useful to a variety of stakeholders. As more stakeholders become educated about processes and consequences of changing reservoir operations, collaboration among groups may leverage the support needed to accomplish a holistic management approach. The reservoirs used in this study were in the Yazoo River Basin in Northwest Mississippi. Impoundments are operated by the USACE. I believe the results presented here are representative of many USACE projects, and also have application to other agencies involved with water resource management (e.g., Bureau of Reclamation, Tennessee

Valley Authority, and Bonneville Power). This thesis provides science-based tools for a reservoir management toolbox to improve collaboration and communication between natural resource managers and reservoir operators.

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APPENDIX A

SAS PROGRAM USED TO GENERATE RISK-BASED WATER LEVEL CURVES

The user must change: source data files in lines 2 and 27; volume-water level equation parameters in lines 4, 21 and 23; applicable number of days for estimating moving sums in line 10.

```
1  data waterlevels;
2  infile "c:\waterleveldata.csv" dlm=',' firstobs=2;
3  input wl doy year;              *reads data file with three variables - water level, day of
year(i.e., 1-365), year;
4  v=exp(-46.7)*(wl**13.8);        *lake-specific equation to compute volume (v) at each water
level;
5  Lwl=lag1(wl);                  * computes a new variable, Lwl, representing wl lagged 1
day;
6  Lv=lag1(v);                     *computes a new variable, Lv, representing v lagged 1 day;
7  Cwl=wl-Lwl;                     *computes daily change in water level;
8  Cv=v-Lv;                        *computes daily change in volume;

9  proc plot;plot Cwl*doy Cv*doy;
10 proc expand out=A;convert Cv=CvN/ transformout=(movsum 60); *computes CvN from Cv
as the N-day moving sum (N = 60 d in theexample);

11 data B;set A;
12 x=(2*3.1416*doy/365);                               *computes x as defined in equation 1;
13 x1=cos(x); x2=sin(x); x3=cos(2*x); x4=sin(2*x); *computes variables x1-x4 needed to
estimate b0-b4 in equation 1;

14 proc quantreg;model CvN = x1 x2 x3 x4 / quantile=0.975; *fits equation 1 through
the 97.5 percentile of 60-d volume increases;
15 output out=C predicted=P;
16 test x1/wald; test x2/wald; test x3/wald; test x4/wald; *tests if x1-x4 contribute
to model; user may exclude non-contributing variables;

17 proc plot;plot P*doy='*' CvN*doy='.'/overlay; *produces scatterplot and overlaid 97.5
percentile shown in Figure 3;

18 proc sort;by doy;
19 proc means noprint;var P;output out=D mean=P;by doy; *reduces the multiyear dataset
to an average 365 day year;

20 data E; set D;
21 spillV=exp(-46.7)*(69.5**13.8);      *computes volume or reservoir at spillway elevation
(69.5);
22 safeV=spillV-P;                      *volume at spillway elevation minus the 97.5
percentiles 60-d rise predictions from quantreg procedure;
23 safeWL=exp((log(safeV)+46.7)/13.8); *water level corresponding to safeV estimated by
solving for wl in the volume-water level equation used in line 4;
24 proc sort;by doy;

25 data rulecurve;
26 infile "c:\rulecurve.csv" dlm=',' firstobs=2;
27 input doy ruleWL; *reads data file with two variables - day of year (i.e., 1-365), water
level prescribed by existing rule curve;
28 proc sort;by doy;

29 data F; merge E rulecurve;by doy;

30 proc plot; plot safeWL*doy='p' ruleWL*doy='r'/ overlay; *produces the curves shown
in Figure 4;
31 run;
```