OPTIMAL ALLOCATION OF RESERVIOR WATER:

A CASE STUDY OF LAKE TENKILLER

By

DEEPAYAN DEBNATH

Master of Arts
University of Kalyani
West Bengal, India
2005

Submitted to the Faculty of the
Graduate Collage of the
Oklahoma State University
in the partial fulfillment
of the requirements
for the degree of
MASTERS OF SCIENCE
December 2009

OPTIMAL ALLOCATION OF RESERVIOR WATER:

A CASE STUDY OF LAKE TENKILLER

Thesis Approved:

Dr. Arthur Stoecker
Thesis Advisor

Dr. Tracy Boyer

Dr. Larry Sanders

Dr. Brain Whitacre

Dr. A Gorden Emslie
Dean of the Graduate collage

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude and respect to my advisor Dr. Arthur Stoecker for his patient supervision and guidance that made this work possible. He helped me throughout the entire process of this research thesis.

My gratitude also goes to my committee members, Dr Tracy Boyer, Dr Larry Sanders and Dr Brain Whitacre. Their support and encouragement provided guidance throughout writing this thesis.

I am grateful to the Oklahoma Water Resources Research Institute (OWRRI), Oklahoma Water Resources Board (OWRB) and U.S. Geological Survey (USGS) for financially supporting this research thesis. The generous services of Gracie Teaque in formatting this thesis are greatly appreciated.

I would also express my gratitude to my uncle Sudhir Debnath without his love, inspiration and financial help it would not be possible for me to complete this thesis. My parents, Saraswati Debnath and Nityananda Debnath and brother Debjit Debnath, provided my needed guidance and support throughout my life and educational endeavors. For this I am eternally grateful to them.

Thanks to all of my friends in Stillwater who were with me throughout the entire period of my graduate studies and gave me complete support during the process of writing this thesis.

I would like to thank the Department of Agricultural Economics and the College of Agricultural Sciences and Natural Resources. The faculty and staff are always helpful and they are like my family members. I would like to give a special thanks to Dr. Francis Epplin, who will always have a special place in my career in this department. I will always cherish the friendships of many graduate colleagues in the Department of Agricultural Economics

Finally, I want to express my sincere appreciation to my grandmother Biva Debnath whose unending love and support make this work possible. Thanks grand ma.

DEDICATION

This thesis is dedicated to my beloved mother Saraswati Debnath. She is everything in my life.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

PROBLEM STATEMENTS AND OBJECTIVES

Introduction

‘Water has an economic value in all its competing uses and should be recognized. Managing water as an economic good is an important way of achieving efficient and equitable use, and of encouraging conservation and protection of water resources’ --- *The Dublin Statement on Water and Sustainable Development*.

The use of water resources is very important to mankind, ranging from commodity type benefits in agriculture, industry and households to environmental values, including biodiversity and recreation. The unique characteristics of water such as hydrological and physical attributes, water demand, social attitudes, and legal-political considerations make it a truly unusual resource. For numerous physical, economic, social and political reasons, it presents special challenges in measuring the benefits accruing from different uses.

The determination of different benefits obtained from water usually call for special management approaches; it would be useful to group the type of values into two classes. These are (a) consumptive benefits which include residential and industrial uses, agricultural uses and waste load dilution (b) non-consumptive benefits which include recreational value, biodiversity, fish and wildlife habitat, flood control and power generation. They are characterized by increasing scarcity and the associated problem of allocation among competing uses to maximize economic value.

Problem Statement

The scarcity of water resources is one of the most pervasive natural resource allocation problem facing water users and policy makers. Water scarcity has become an important constraint on economic development, which results in fierce competition for water resources between economic sectors that rely upon it (Winpenny, 1994; (World Bank/ELB, 1990)). Throughout the world, with the growth in population and income, the demand for water for both consumptive and non-consumptive uses is increasing. In the recent decade, the biggest challenge for the policy maker is addressing the water management problem. In the context of water management, decision makers in the arid and semi-arid states face a question about how much water should be allocated among competing uses such as hydroelectric power generation and municipal and industrial uses versus how much water should be stored for recreational uses.

The problem of water allocation has become more complicated since water markets are absent or do not operate effectively as it is essential to life. Clean water and sanitation are also essential for good health. Many people intuitively reject pricing of a resource (water) that is necessary for life, some cultures or religions prohibit water allocation by market forces (Faruqui et al, 2001).

A reservoir may be actively managed with respect to hydropower, flood control, irrigation and public water supply uses while recreational uses are often treated as residual. Though water use for recreation is non-consumptive, it is sensitive to the lake level and, thus it competes with water released for hydropower and other uses. Now the question is “How much water should be traded off between private uses and recreational uses in order to maximize net social benefits?”

The problem of water management is of current relevance in Oklahoma mainly due to the rising population and increasing competition among different uses such as: public water supply, agriculture, recreation, fish and wildlife, navigation, hydropower, etc. In the recent decades, Oklahoma Water Resource Board (OWRB) and other state agencies face a severe challenge to assure a safe and reliable supply of water to meet both the consumptive and non-consumptive needs of all Oklahomans. It requires an effective and comprehensive plan to meet the future water supply challenges. In the future, the water should be managed in such a way that would best serve the different kind of needs of all the people of Oklahoma. Therefore, a comprehensive water management plan is required. The major goal of the new water management plan for Oklahoma is to provide safe and dependable water supply for all Oklahomans and also provide information so that water providers, policy-makers, and water users could take the best decision concerning the use and management of Oklahoma’s water resources. This research thesis will develop a decision support tool that will help in managing reservoir water while allocating it among multiple uses. Finally, it will come up with alternative reservoir management scenarios that will simultaneously consider the consumptive and the non-consumptive uses of reservoir water.

General Objective

The overall objective of this study is to determine the optimal allocation of Lake Tenkiller water among competing uses: (1) Hydroelectric power generation (non-consumptive uses), (2) Urban and rural water supply (consumptive uses) and (3) Lake recreational values (non-consumptive uses) over the period of twelve consecutive months that would maximize the net social benefit.

Specific Objective

The specific objectives are:

1. Determining the monthly release pattern of water from the reservoir for different purposes that would maximize the net social benefits.
2. Determining the optimal monthly lake level explicitly considering the flood control capacity and in-stream needs.
3. Determining the benefits arising from each of the following uses:
    - Hydropower Generation
    - Urban and Rural Water Supply
    - Lake Recreational Uses
4. Estimate the monthly urban and rural water demand.
5. Estimate the monthly lake visitation.
6. Estimate the amount of monthly hydroelectric power production.

CHAPTER II

LITERATURE REVIEW

This section contains a review of the past literature concerning the reservoir management issues. First, studies related to efficient allocation of reservoir water among competing uses with different needs and demands are reviewed. Second, literature on consumptive and non-consumptive uses of reservoir water is discussed. The last section is a review of management policies that are generally used for allocating surface water supplies.

Studies Related to Water Allocation

Several optimization models have been developed for addressing the problem of optimal allocation of reservoir water among multiple uses. Water allocation has received considerable attention in the recent past by the scientific community. Bielsa and Duarte (2001) developed an economic model for allocating water between two competing sectors, namely irrigation and hydropower in northeastern Spain. Their study addressed the conflict between the different water users mainly among the irrigation and hydropower use of the reservoir water. They proposed an optimum allocation model that maximizes the joint profit of both irrigation and hydropower uses based on the water rights. Their study mainly considered and proposed a resolution process for a conflict that arises in the allocation of water within a territory, and among the competing uses that were regulated in different time periods. They showed that the optimal allocation was one that mitigated losses in the dry periods, and concluded that in order to increase the joint profit the surface area under irrigation should be extended. The major strength of Bielsa and Duartes' study was the discussion of the optimal allocation of reservoir water among competing uses through the introduction of the joint profit maximization function. At the same time, their study only focused on the market uses of water. However in their study non-market uses like the recreational values are not considered.

Qubáa et al. (2002) developed an optimization model that allocates water resources among and between the competing sectors in order to obtain the highest economic returns. A linear programming model was developed to allocate water between the irrigation and municipal sectors that generate highest net return subject to the constraints on land and water availability. In the irrigation sector, water was allocated among different types of seasonal crops and monthly uses of land while at the same time the monthly municipal water supply was determined based on the population served under the system.

Similar work was done by Chatterjee, Howitt and Sexton (1998). They examined the trade-off between agricultural water use and water released for hydroelectric power generation. A dynamic optimization model was used to determine the optimal release of reservoir water for irrigation and hydropower production in the western United States. They argued that water should be released if the value of releasing water for hydropower generation and irrigation was higher than the value of storing water for other purposes. The result of their study showed that shifting the months of releases of water for irrigation, increase the head of the reservoir and thus generate more hydropower during the summer month of peak electricity demand. This would definitely increase the total revenue generated to the economy. The recreational use of water stored in the reservoir is not discussed.

Ward and Lynch (1996) developed ‘An Integrated Optimal Control Model’ that maximized the social benefits arising from allocating reservoir (river basins) water among lake recreation, in-stream recreation and hydroelectric power generation uses. They showed an optimal management policy could yield more net benefits than the historical management policy. They found that water released for hydropower generation yielded higher benefits than managing lake volumes for recreation. In their analysis, they only considered the non-consumptive uses such as reservoir recreation, in-stream recreation and hydropower production. However, in my research study along with non-consumptive uses, consumptive uses such as urban and rural water supply uses are also considered.

Babel, Gupta and Nayak (2005) in their study, developed a simple ‘Interactive Integrated Water Allocation Model’ (IWAM). The objective of their model was to maximize the net economic returns to the users. Deterministic linear programming was used to solve the optimization problem. Their study considered six different water using sector: agriculture, domestic, industry, hydropower, recreation and environment. Individual demand function of each sectors were estimated and included together in the programming model. They used weighting technique and simultaneous compromise constraint technique to combine multi-objectives into a single objective function. In my research study non-linear programming technique is used for allocating reservoir water and only three different sectors such as hydroelectric power generation, lake recreation and urban and rural water supply are considered.

Consumptive and Non-consumptive Uses of Reservoir Water

Reservoir water is used for many purposes. The water uses are categorized mainly into two groups: consumptive and non-consumptive uses. The consumptive water uses include municipal and industrial water supply and irrigation. Non-consumptive uses include hydro-electric power generation, flood control and recreational uses like fishing, boating, and wildlife habitat. There are many previous studies that considered the consumptive and non-consumptive uses of reservoir water separately. Some of these studies are reviewed here.

Stephen E. Draper (2002) provided the definition of consumptive and non-consumptive uses. According to Draper, the water that was consumed and not reused was considered as consumptive uses such as drinking water supply use. While the non-consumptive water uses meant that, water was simultaneously used for multiple uses but not consumed or reduced in quantity. More specifically the non-consumptive uses of water allowed additional downstream uses while consumptive did not. Finally, he concluded that the available water resources should be best used if the policy makers clearly classified the water among these two categories.

Shrestha et al (1996) developed a fuzzy ruled based model for allocating reservoir water among different consumptive and non-consumptive uses such as hydropower, municipal and industrial water demand, flood control use and recreational demands. The fuzzy model was operated on the basis of ‘if’ and ‘then’ principles that is; ‘if’ the current elevation was above certain level ‘then’ there were release of a certain amount of water. However the rules lead to mechanistic release pattern based on certain purposes while the value derived from these releases were obscured. They also considered Lake Tenkiller for their study.

Bachrach and Vaughan (1994) in their unpublished paper estimated the household water demand. They estimated a Marshallian demand function based on price and income. Finally they concluded that in order to derive the water demand function data of more than one locality over a single period of time or more than one period of data over a single locality was required.

Aribisala (2007) developed a water forecasting model for hydroelectric power generation. The amount of hydroelectric power generation mainly depended on the amount of water released and the head of the reservoir which was a function of the inflows. He used econometric tools to forecast the water released for hydroelectric power generation over the period of twelve months from January to December. He found that from 1970 to 1987 for the Kanji hydropower station the reservoir storage was less during the summer months, because of the peak electricity demand.

Hanson, Hatch and Clonts (2002) in their paper described how the reservoir recreational values changed with the lake level. They studied the impact of the monthly lake levels on the recreational values. The contingent valuation method was used for estimating the impact of water level changes on the recreational values. They found that during the summer months when the recreational benefits were valued most, high lake level should be maintained. The authors found that, during the summer months, if the lake level was decreased by one foot then there was a 4 to 30 percent decrease in recreational expenditure. The major drawback of this study was that they did not consider different scenarios and the huge range of decrease in recreational value was not at all feasible.

Reservoir Management Issues and Policies

The management of reservoir water is a crucial issue for a particular reservoir to meet the future demand with the rising population and income. It is also persistent in Oklahoma. There are numerous studies that discuss reservoir management. The primary focus of this part is to discuss the previous studies related to reservoir management.

Ralph A. Wurbs (1997) discussed the multiple beneficial uses of reservoir storage such as municipal and industrial water supply, irrigation, hydroelectric power generation, and navigation. He also discussed that in most of the cases water was considered as public good and its allocation was based on water rights. He noted that the use of optimization model for allocating the reservoir water could definitely increase the overall societal benefits. He also mentioned that the decision support model (a computer programming model) was a very important tool in managing the reservoir water and allocating it among multiple uses. Wurbs only summarized the policies for managing reservoir water. However, he did not discuss how to manage the multiple uses of a reservoir that would maximize net social benefits.

George et al (2007) discussed that with the increase in competition among different water uses the greatest challenge to the water resource managers was to match the limited amount of available water between the demand and supply. They introduced an integrated hydro-economic model in order to discuss this issue. Finally, they developed an alternative scenario of allocating water based on the cost benefit analysis of different users. This work was very encouraging in the context of the water management issue. The major drawback of this work was that they did not consider the non-market uses while managing the reservoir. In the recent decades, the non-market uses including the recreational values were a major concern of the lake reservoir management. Thus, further research was required for allocating the reservoir water considering the recreational values for that particular reservoir.

Carriker (1984) in his paper raised the question “who gets to use how much for what?” With the increase in population and economic growth there was a severe increase in the water demand. This generated competition between water use for agriculture and other water uses mainly public water supply. He also mentioned that with the increasing demand for water the abundant water resources become scarce resources and the biggest challenge for the policy makers is to distribute this scarce resource among different uses. The water policy issue was more complex since it varies from place to place. He finally concluded that water rights under legal framework based on the water demand and supply of a particular region was the best solution for allocating water among competing uses. The major drawback of allocating water based on water rights was that it does not account for the non-market values of reservoir water.

Mckenzie (2003) developed a model on the Broken Bow Lake in Oklahoma based on the methodology developed by Re Velle (1999). His model was developed to consider the possibility of water sales subject to recreational, flood control, municipal and industrial water uses and hydroelectric power generation and minimal water release. In his dissertation, he mainly compared the current management practice of the reservoir with the optimization model results under different scenarios. He found that the use of an optimization model would increase the total benefits. Mckenzie’s study was very much relevant in the context of this research. The current research study would implicitly consider hydroelectric power generation, urban and rural water supply and lake recreational benefits while flood control and in-stream lake recreational benefits were explicitly considered. These were the major difference between my study and Mckenzie's.

Kadigi et al (2008) explained that the problem of water management and allocation could be resolved only by knowing the value of water among its competing uses. They argue as to whether water should be considered as an economic good or a social good. In Tanzania, Great Ruaha River Catchment (GRRC) water was used for irrigation and hydropower production. The estimated value of water used for irrigation and household consumption were 15.3 Tanzanian shilling (Tsh)/m^3 and 0.19 Tsh/m^3 respectively, while the value of water used for hydropower production were ranging from 59 to 226 Tsh/m^3. But water used for irrigation support the livelihoods of around 30,000 agrarian families living in the GRRC. Therefore the allocation procedure should be completely based on the value of water among its users. Thus, the policy makers should be well-informed about the value of water based on the users.

CHAPTER III

CONCEPTUAL FRAMEWORK

A model determining the optimal allocation of reservoir water among consumptive and non-consumptive uses was constructed. The model considered two non-consumptive uses: (a) hydroelectric power generation and (b) lake recreational values and one consumptive use, urban and rural water supply. It was then used to maximize the total benefits accruing from the reservoir water use over a twelve month period from January through December of a particular year. This study would also consider how the lake volume was distributed among different uses in order to achieve the maximum total benefits.

Total Benefits

In order to optimally allocate reservoir water among multiple uses, the total benefits derived to the society should be calculated. The total benefits arising from the lake reservoir depend on both the consumptive and the non-consumptive uses. It was calculated by summing up all the benefits accruing from particular uses over the twelve month period.

The total benefit is calculated as follows:

$$\text{Total Benefit} = \sum_{m=1}^{12} (BH_m + BM_m + BR_m)$$

Where,

BH_m: Benefit accruing from hydroelectric power generation in month *m*

BM_m: Benefit accruing from urban and rural water supply in month *m*

BR_m: Benefit accruing from lake recreational uses in month *m*

Non-Consumptive Uses

Two non-consumptive uses of the reservoir water were mainly considered in this research study. They were: (a) hydroelectric power generation and (b) lake recreational uses.

The generation of hydroelectricity depends on the amount of water released for hydropower generation and the average lake level (head) over the months. The hydroelectric power generation function was as follows:

$$\text{Hydroelectricity Produced}_m = f\,(\text{Volume of water released}_m, \text{Head of the reservoir}_m)$$

Where, hydroelectricity produced in each month was in Megawatt hours, volume of water released for hydroelectric power production in each month was measured in acre feet and reservoir head for that particular month was measured in feet. The reservoir head was the height of the water above the turbine and, it was calculated as the difference between the turbine and the current lake level. The greater the head of the reservoir more force will be applied to the turbine and thus more electricity will be produced.

The Lake recreational visitation of the reservoir water mainly depends on the lake level, where the lake level was in acre feet. And, it was represented as:

$$\text{Lake Recreational Visitation}_m = f(\text{Lake Level}_m)$$

Where, *m* was the month

It was found that the Lake visitation was maximum at the normal lake level of 632 feet and it would reduce below and above the normal lake level. The winter month's visitation was not sensitive to the lake level. Thus, during the winter months from October through March there were constant number of visitors. Finally, the monthly recreational values were determined by multiplying the value of visitors per day by the monthly visitation.

Consumptive Uses

The consumptive use was mainly concerned with the urban and rural water supply uses. The value of the water consumed by the local communities of the surrounding area was determined by calculating the net social welfare derived from the urban and rural water use. The Net Social Welfare (NSW) was the area under the demand curve and above the supply curve. It was represented as:

$$\mathrm{NSW}_m = \mathrm{CS}_m + \mathrm{PS}_m$$

Where, NSW_m = Net Social Welfare for month m,

CS_m = Consumer Surplus for month m

PS_m = Producer Surplus for month m

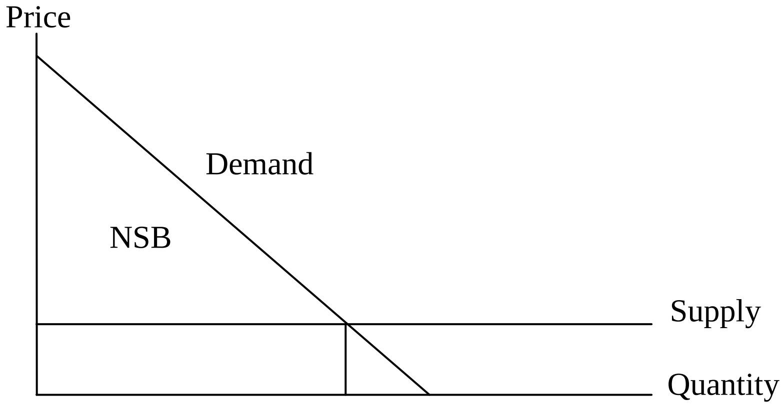

Figure III-1 Net Social Benefits Arising From Rural Water Use

It was assumed here that supply of rural water was perfectly elastic. And, thus the NSW was obtained just by integrating the price flexibility form of the ordinary demand function, since in the case when the supply curve was horizontal (i.e. perfectly elastic) then there was no producer surplus. The price flexibility form of the ordinary (Marshallian) demand function was used here.

Marshallian demand equation for monthly urban and rural water use was represented as:

$$Q_m = d_m + D_m * P_m$$

Where, Q_m – Quantity demand for water in each month

P_m – Price of water in each month

d_m & D_m – the intercept and slope of the demand curve

The corresponding price flexibility form was represented as:

$$P_m = \alpha_m + \delta_{m*} Q_m$$

Where, $\alpha_m = - d_o * D^{-1}$ and $\delta_m = D^{-1}$

The slope (dp_m/dq_m) of the above equation was calculated from the price elasticities, i.e (dq_m/dp_m)*(P_m/Q_m) and the intercept was calculated as:

$$\alpha_m = P_m - \delta_{m\,*}\, Q_m$$

Finally, the net social welfare derived from the urban and rural water use for each month was determined by integrating the price flexibility form of the demand function over quantity of water demanded in each month and subtracting the pumping cost (supply function) of water in each month. And, it was represented as:

$$NSW_m = \int_0^{Qm}(\alpha_m + \delta_{m*}\, Q_m)dQ_m - (C_0 + C_1Q_m)$$

CHAPTER IV

DATA REQUIRMENT AND METHODS OF ANALYSIS

Data Collection

Tenkiller Ferry Lake and its surrounding area of northeastern Oklahoma had been chosen for this study. Daily data on the lake inflows, releases for power and spillage, the amount of power generated, lake levels, precipitation and evaporation from year 1995-2007 were obtained from U.S. Army Corps of Engineers website (USACE, 1995-2007): http://www.swt-wc.usace.army.mil/TENKcharts.html and WCDS Tulsa Districts U. S. Army Corps of Engineers Historical Generation Data website (UASCE, 1995-2000): http://www.swt-wc.usace.army.mil/PowerGen.html. The USACE also provided monthly visitor data for the same period. Monthly electricity prices were obtained from the U.S. Department of Energy Information website (2008). Data concerning the Rural Water System (RWS) uses and prices charged were obtained from Oklahoma Water Resources Board (OWRB) and various municipal water districts. The OWRB also provided GIS shape files of RWS pipelines and facilities. These were used to develop a hydrologic simulation models for 15 communities' water systems that were using Lake Tenkiller water. EPANET2 software obtained from EPA website: http://www.epa.gov/nrmrl/wswrd/dw/epanet.html was used to run this simulation. This hydrologic simulation software was used to estimate pumping cost under alternative population levels. Finally, survey data (Boyer et al. 2008) were used to apply recreational values to visitor numbers according to the lake level.

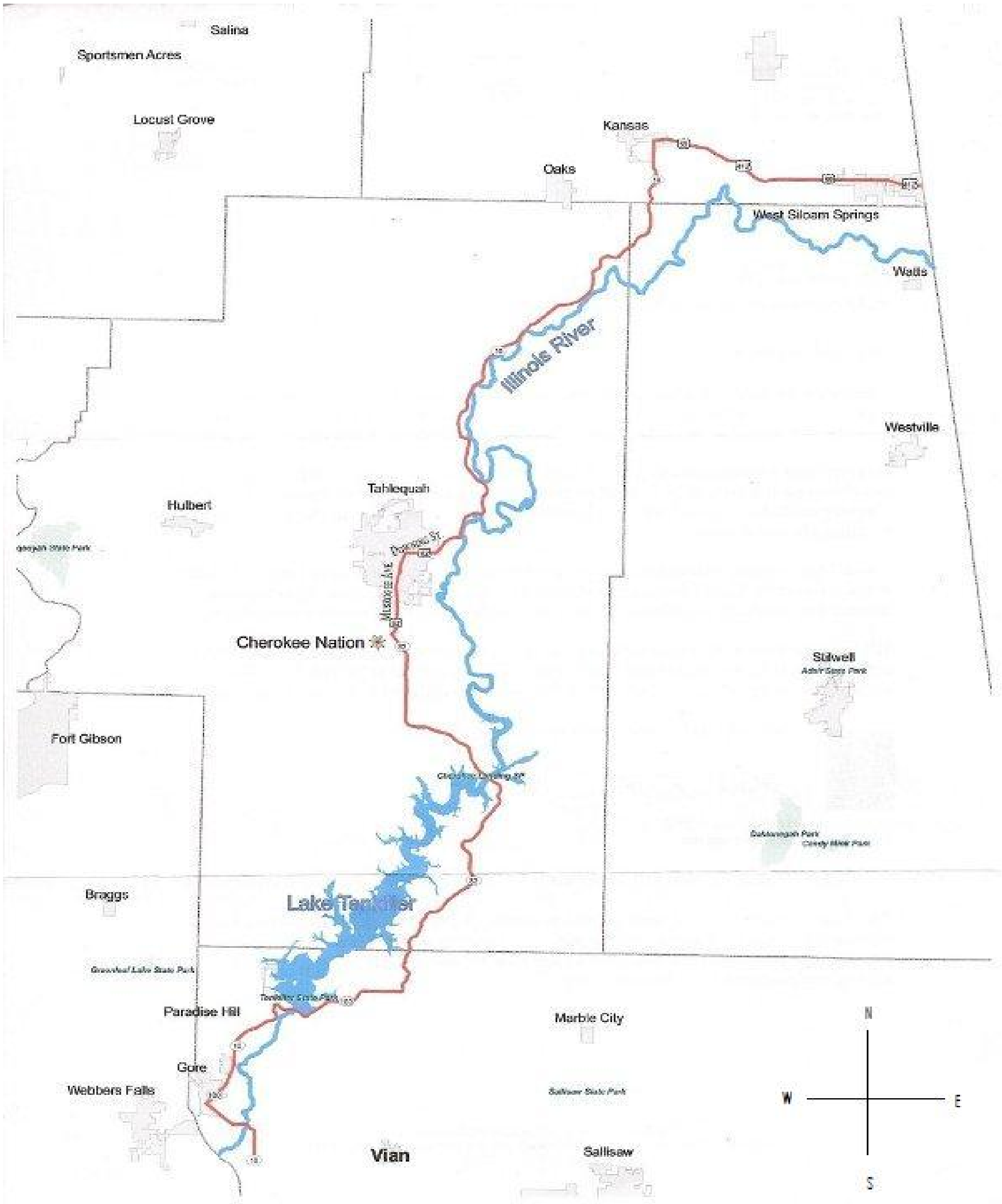

Figure IV-1 Tenkiller Ferry Lake
(source: http://www.laketenkiller.com/sites/tenkiller/uploads/images/Bypass1.jpg)

Model Specification

The general objective of this study was to optimally allocate reservoir water among multiple (consumptive and non-consumptive) uses and examine the effect of several water management strategies for the lake reservoir that would maximize the total benefits arising from multiple uses. The accomplishment of this objective required determining the total benefits arising to the society from both consumptive and non-consumptive uses of the reservoir water. The model was completely based on the mass-balance approach; the volume of water at the end of each month was equal to beginning volume for the next month.

A flowchart representing both the hydrologic and the economic characteristics of the model was presented below:

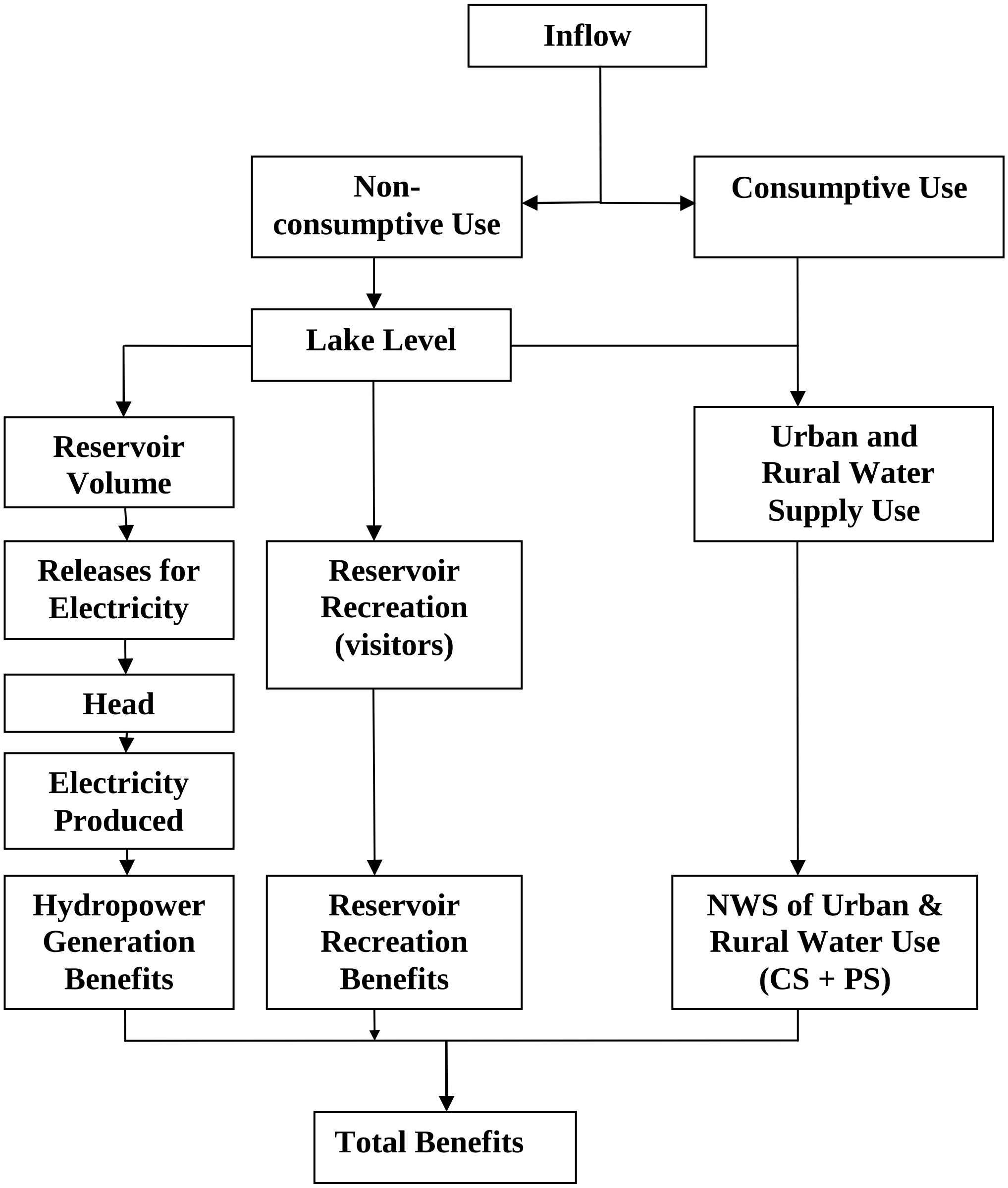

Figure IV-2 Flowchart Illustrating The Model

As showed in the schematic representation (Figure IV-2), the total inflow of the water was distributed among consumptive and non-consumptive uses. The non-consumptive uses were further sub-divided into non-market lake recreational benefits and market priced hydroelectric power generation benefits. The lake recreational benefits depend on the lake level and the visitors' days, while the hydroelectric power generation benefits depend on the amount of water released for this purpose and the benefits arising from urban and rural water supply uses depend on the water demand of that particular area (i.e. the area under the demand curve and above the supply curve). The hydroelectric power generation benefits also depend on the effective head of the turbine which was derived from lake elevation and the height of the top of the turbine.

Mathematical Formulation

A deterministic non-linear programming technique was used to find the optimal allocation of reservoir water among consumptive and non-consumptive uses. A non-linear programming model was developed to allocate Lake Tenkiller water among competing uses based on inflows, on-peak and off-peak demand for hydroelectricity, urban and rural water supply and recreational uses over the different months of a particular year. The model was developed and solved in General Algebraic Modeling System (GAMS) with the MINOS solver for the year 2010. It was mainly varied with the volume of water stored and the amount of water released over the twelve month time horizon from January to December so that the total net social benefits over that particular period were maximized. The model considered two non-consumptive uses; hydroelectric power generation and recreational values and one consumptive use; urban and rural water supply. A mass balance equation was used to determine the level and volume of water in the lake that equated the inflows and outflows in each period. According to the United States Army Corps of Engineers (USACE) the top of the flood control pool was 667 feet above sea level (FASL). The maximum monthly lake level was constrained to be around 645 FASL to maintain flood control capacity of the reservoir. The reservoir storage volume and the inflows were obtained from the USACE website from the period 1995 to 2007. In the website the lake level data were given in feet, while the lake volume was given in acre feet. Inflows and releases for power generation data were given in DSF and it was converted into acre feet by using the conversion factor 1 AF =1.983439*DSF obtained from USACE website. The evaporation and rainfall data were converted from inches to acre feet based on the estimated surface area of the lake. The optimization model endogenously determined the monthly release patterns for each uses based on the average lake volume at the beginning month of January and average inflows for each months from January through December for the year 1995 to 2007.

The optimization model maximized the sum of net monthly social benefits arising from hydroelectric power generation, urban and rural water supply and lake recreation. The model was specified as:

Maximize:

$$\text{Total Benefit} = \sum_{m=1}^{12} (\text{Hydroelectric Power Generation Benefits}_m + \text{Rural Water Supply Benefits}_m + \text{Lake Recreational Benefits}_m)$$

Subject to

$$\text{Volume}_{m+1} = \text{Volume}_m + \text{Inflow}_m - \text{Outflow}_m - \text{Evaporation}_m$$

$$\text{Volume}_{min} \leq \text{Volume}_m \leq \text{Volume}_{max}$$

$$\text{Outflow}_{min} \leq \text{Outflow}_m$$

$$\text{Volume, Inflow, Outflow} \geq 0$$

*subscript *m* represents each month
max and *min* represents the maximum and minimum volumes in month *m*

Relationship between Lake Level and Lake Volume

GAMS required a simple and smooth equation to calculate the lake level and volume relationship. Lake level (feet) and the volume of water (acre feet) data were obtained from the USACE website was used to estimate a simple quadratic equation by using Ordinary Least Square (OLS) method over the range of 630 to 645 feet of depth. The estimated equation was as follows:

$$\text{Lake Level (ft)} = \underset{(844.17)}{0564.56} + \underset{(68.08)}{0.00012870}\text{Vol (acre feet)} \underset{(-29.39)}{-3.9105*10^{-11}} \text{Vol}^2 \text{ (acre feet)}$$

$R^2 = 0.99$ for 3119 observations and t-values were in parenthesis

Mass Balance Equation

The major part of this model was the mass balance equation that made the model work. It worked according to the law of physics, i.e. volume of water in the current period was determined from the volume of the water in previous period, inflows, outflows, evaporation, rainfall and seepage. The mass balance equation was the one that determined the volume of reservoir water for each month and the variation in storage from month to month. Mathematically, the mass balance equation was represented as:

$$V_{m+1} = V_m + I_m - O_m - E_m$$

Where,

V_{m+1} : Volume of water in the reservoir in the month *m+1*

V_m : Volume of water in the reservoir in the month *m*

I_m : Inflow of water including rainfall in the reservoir in the month *m*

O_m : Outflow of water from the reservoir including releases for power production, urban and rural water use and other uses in the month *m*

E_m : Evaporation and seepage from the reservoir in the month *m*

The historical monthly average lake volume data and the average inflow and outflow for each month over the period of November 1994 to March 2007 were obtained from USACE website and were given below.

Table IV-1 Historical Average Monthly Lake Level, Volume, Inflow And Outflow Of Water For The Year 1995 Through 2007

Month	Lake Level (Ft)	Lake Volume[a] (Ac Ft)	Inflow[b] (Ac Ft)	Release Power (Ac Ft)	Other Release (Ac Ft)	Evap. & Seepage (Ac Ft)
Jan	633	644,642	139,529	86,551	38,101	5,517
Feb	632	654,002	115,159	82,287	9,345	14,776
Mar	633	662,784	134,488	100,303	23,780	6,055
Apr	633	667,134	152,338	104,362	25,362	14,218
May	635	675,530	141,149	86,434	30,778	15,956
Jun	635	688,511	132,882	70,359	22,275	15,446
Jul	634	713,313	65,106	83,979	11,902	11,902
Aug	630	642,554	27,618	53,020	39,984	7,433
Sep	628	606,589	35,776	21,650	3,130	9,477
Oct	628	608,972	34,665	29,806	2,168	1,577
Nov	620	610,106	95,504	49,364	6,846	9,497
Dec	631	639,903	93,730	75,611	8,231	5,149

[a] beginning volume of each month, [b] including rainfall

Source: http://www.swt-wc.usace.army.mil/TENKcharts.html

Estimation of Hydroelectric Power Generation Benefit

The economic benefit arising from hydroelectric power generation was obtained by multiplying the amount of electricity produced in a particular month to the price of electricity of that particular month obtained from U.S. Department of Energy for the year 2000 through 2008. The average monthly electricity prices of Oklahoma were given in the following table:

Table IV-2 Average Monthly Electricity Price (2000-2008)

Month	Price[a]
Jan	89.00
Feb	89.00
Mar	89.00
Apr	89.00
May	90.50
Jun	94.70
Jul	96.60
Aug	96.50
Sep	94.10
Oct	91.20
Nov	88.00
Dec	88.00

[a]- prices in US$ per MWH
source: *http://www.eia.doe.gov/cneaf/electricity/epm/table5_6_b.html*

Thus, the total benefits derived from the hydroelectric power generation were represented as:

$$BH_m = Price_m * MW_m$$

Where,

BH_m : Hydroelectric power generation benefit in month *m*

$Price_m$: Price of Per 1000 Kilowatt hour electricity in month *m*

MW_m : Amount of electricity produced (Megawatt Hour) in month *m*

In the previous chapter, hydroelectric power generation benefits were considered as a function of volume of water released from the reservoir for this purpose (acre feet) and the effective head of the reservoir (feet). This functional form was based on the ReVelle’s (1999) formula where power generation was a nonlinear function dependant on the product of water released in acre feet and head measured in feet above the turbine. The function was expressed as:

$$MW_m = aR_mH_m$$

Where,

MW_m = amount of electricity produced in Megawatt Hour in month m

a =constant reflecting gravity, viscosity, and turbine efficiency

R_m = volume of water released through the turbines in month m

H_m = Head i.e. height of the water above the turbine in month m*

Daily water released data for the hydroelectric power generation and data of the amount of electricity produced over the period of January 1995 through December 2000 were obtained from USACE website. The average lake level of each day for this period was calculated using the lake level and volume relationship. The required head for that particular day t was then calculated as ($level_t - 502$). The height of the top of turbine was given as 502 feet above the sea level. Finally, the calculated head was multiplied with the amount of water released for each month.

Water released for hydropower generation and head were considered as the explanatory variables. OLS method was used to estimate the hydroelectric power generation equation. The estimated equation was as follows:

$$MW_m = \underset{(1152)}{0.232457}\text{Head* Released (acre feet)}$$

$R^2 = 0.99$ and t-value was in parenthesis

In the optimization model, the above mentioned relationship was used to calculate the amount of electricity produced in each month. Further, it was assumed that for a single day turbine worked for about 11 hours in order to produce electricity and by dividing the megawatt hour of electricity produced by 3960 (horsepower unit) the amount of monthly hydroelectricity production was calculated. The maximum capacity of the generator was approximately 70 Megawatt Hours (Warner et al, 1973), while a minimum of around 2 Megawatt Hours of electricity was produced.

Estimation of Urban and Rural Water Supply Benefit

John Boland (1997) explained a basic water demand model depending on the population and it followed as:

$$Q = b*P$$

Where,

Q = average daily aggregate water use

P = resident population in service area

b = per capita water use

The quantities of water treated monthly and wash water (contaminated, containing ammonia and nitrates) data for the six cities: Muskogee, Muldrow, Sallisaw, Gore, Eufaula and Roland over the period of seven years from 2001 to 2007 were obtained from Oklahoma Department of Environmental Quality (ODEQ) office. Population data over the same period for those cities were obtained from the United States Census. Monthly per capita water demand was then calculated by dividing the monthly water demand (obtained by subtracting wash water from treated water) by the population of a particular region. Then, the monthly per capita water demand model was estimated considering mean population as an explanatory variable. The model was used to forecast the future monthly per capita water demand based on the population of that region and it was also used to predict the monthly variability of the water demand. Due to lack of availability of several variables such as price, temperature, income, rainfall etc, this kind of simple model was used in my research study. Future forecasting based on this model was not considered as the most perfect one.

A linear hierarchical monthly per capita water demand model capturing both the fixed and random effect was estimated from the time series cross section data. In SAS, *PROC MIXED* was used to estimate this hierarchal model considering city and year as random terms. The estimated water demand equation over the period of 2001 through 2007 was as follows:

$$Qd_m = \underset{(7.82)}{5.2299}*Jan + \underset{(6.71)}{4.4911}*Feb + \underset{(7.09)}{4.7443}*Mar + \underset{(6.76)}{4.5217}*Apr + \underset{(7.58)}{5.0699}*May +$$

$$\underset{(8.1)}{5.4154}*Jun + \underset{(10.08)}{6.7435}*Jul + \underset{(10.12)}{6.7659}*Aug + \underset{(8.78)}{5.8753}*Sep + \underset{(8.34)}{5.5772}*Oct +$$

$$\underset{(7.41)}{4.9563}*Nov + \underset{(7.41)}{4.9540}*Dec + \underset{(4.15)}{1.2411}*Pop$$

Chi^2 = 372.30 for 504 observations and t-values were in parenthesis.

Qd_m = Per capita water demand for each month in 1,000 gallons

Pop = Relative population of a particular city

Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec were the dummy variables which took 1 for that particular month and 0 for other months.

According to the study conducted by USACE (2001), in the northeastern Oklahoma around twenty Rural Water Districts (RWD) obtained water from Lake Tenkiller. Current population data (June 2009) of those RWD were obtained from Safe Drinking Water Information System website and were shown in the Table IV-3:

Table IV-3 Population Distribution Of Lake Tenkiller And Its Surrounding Urban And Rural Water System Area For Year 2009

Urban and Rural Water System (Tenkiller Area)	**Population**
Burnt Cabin	118
Cherokee RWD #1	710
Cherokee RWD #2	1,544
Cherokee RWD #3	2,300
Cherokee RWD #7	980
Cherokee RWD #8	413
Cherokee RWD #13	2,120
Town of Vian	1,445
East Central Ok Wat Author.	1,200
Lake Tenkiller Harbor	100
Muskogee RWD # 4	1,710
Muskogee RWD # 7	750
Paradise Hills, Inc.	270
Sequoyah County Water Asso.	15,719
Sequoyah RWD # 7	2,948
Tahlequah Public works	18,431
Lake Region Electric Development	860
Tenkiller Aqua Park	150
Tenkiller State Park	115
Town of Gore	478

Source: *http://sdwis.deq.state.ok.us*

The population data used in this study vary slightly from those used by Boyer et al (2008) and in this study, it was the assumed that the population for 2009 and 2010 were around the same.

The Figure IV-3 below showed the predicted Gallon Per Capita per Day (GPCD) water consumption by the Lake Tenkiller surrounding area derived from the above equation. During the summer months of June, July, August, and September the GPCD was at its peak.

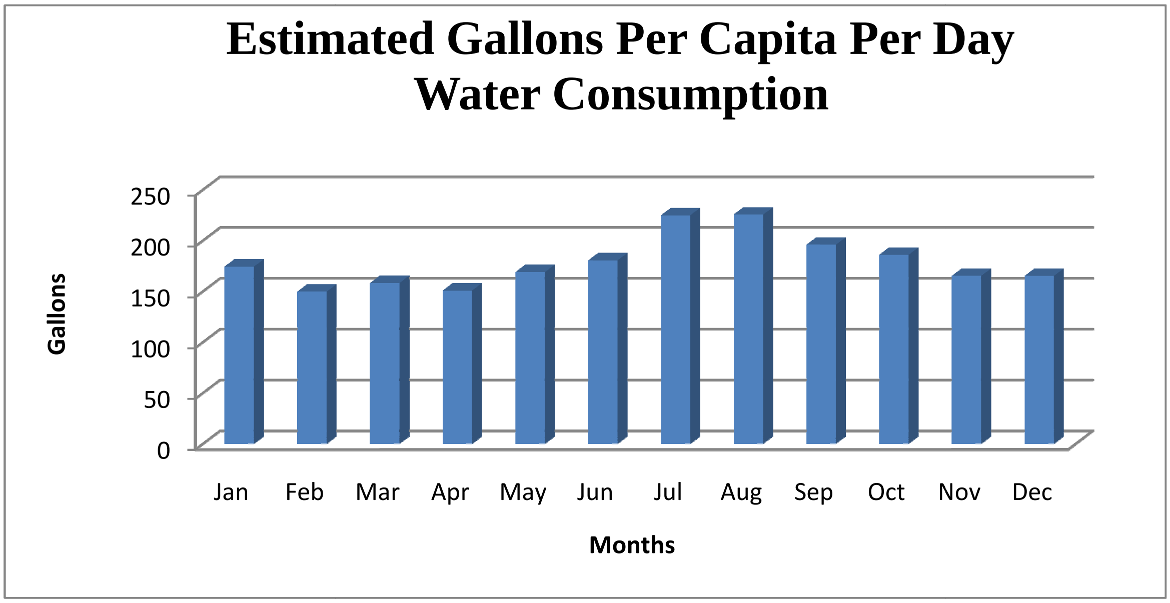

Figure IV-3 Predicted Gallon Per Capita Per Day (GPCD) Water Consumption for each Month by the Lake Tenkiller and its Surrounding Area

A Cobb-Douglas functional form of urban and rural water demand was considered where monthly water consumption for each month was assumed to be related to price as:

$$Q_m = A_m * P_m^{ep}$$

Where,

Q_m = Amount of water consumed in month *m*

A_m= Fixed amount of water consumed in month *m*

P_m = Price of water in month *m*

e_p = Price elasticity of water in month *m*

For this study, the price of water was considered as $3 per thousand gallon of water which was obtained from the Oklahoma Municipal League (2002). The summer and winter price elasticities were considered as -0.25 and -0.04 respectively which were obtained from IRRW Main (Davis et al 1987).

The inverse demand function of water used in each month was calculated based on the amount of water consumed in each month, and the seasonal price elasticity of water obtained from IRRW Main (Davis et al 1987). The price flexibility functional form of the equation was as follows:

$$P_m = \alpha_m + \delta_m * Q_m$$

Where, α_m and δ_m were the monthly intercept and slope of the inverse demand function.

$\alpha_m = P_m - \delta_m * Q_m$

$\delta_m = (P_m/Q_m)*(1/\rho)$

Price Elasticity: $\rho \equiv (dq_m/dp_m)*(P_m/Q_m)$

Table IV-4 Monthly Water Demand, Population, Gallon Per Capita Per Day Water Consumption By Lake Tenkiller And Its Surrounding Area For Year 2009 And The Monthly Slope And Intercept Of Price Flexibility Form.

Month	GPCD	Population[a]	Price Elasticity[b]	Monthly Consumption ('000 gallon)[c]	Intercept	Slope
Jan	174	1,570,830	-0.04	273,843	25,407	-29.06
Feb	150	1,570,830	-0.04	235,158	25,407	-33.84
Mar	158	1,570,830	-0.04	248,416	25,407	-32.03
Apr	151	1,570,830	-0.04	236,761	25,407	-33.61
May	169	1,570,830	-0.25	265,465	4,886	-4.80
Jun	181	1,570,830	-0.25	283,556	4,886	-4.49
Jul	225	1,570,830	-0.25	353,096	4,886	-3.61
Aug	226	1,570,830	-0.25	354,269	4,886	-3.59
Sep	196	1,570,830	-0.25	307,637	4,886	-4.14
Oct	186	1,570,830	-0.04	292,028	25,407	-27.25
Nov	165	1,570,830	-0.04	259,517	25,407	-30.66
Dec	165	1,570,830	-0.04	259,396	25,407	-30.68

[a] obtained from Safe Drinking Water Information System website, [b] obtained from IRRW Main (Davis et al 1987), [c] obtained from Oklahoma Department of Environmental Quality (ODEQ) office

Then by integrating the above inverse demand function the consumer surplus was obtained. Mathematically, it was represented as:

$$CS' = \int_0^{Qm} (\alpha_m + \delta_m * Q_m) dQ_m$$

$$CS' = \alpha_m * Qm + 0.5 * \delta_m * Q_m^2$$

The benefits arising from the urban and rural water supply use was calculated as the net social welfare (summation of consumer surplus and producer surplus) derived from water use. The Net Social Benefits (NSB) arising from the rural water supply use was determined as:

$$\text{NSB} = \text{Consumer Surplus (CS)} + \text{Producer Surplus (PS)}$$

While in this study the water supplied was considered as perfectly elastic (horizontal) and thus there was no producer surplus. Here, the NSB was the area under the demand curve and above the supply curve i.e. CS+PS and it was calculated by subtracting total pumping cost of Q units (acre feet) of water from the above CS' equation. Considering the linear supply function (pumping cost curve), the Net Social Benefits (NSB) arising from urban and rural water supply was represented as:

$$NSB_m = (\alpha_m Q_m + 0.5*\delta_m* Q_m^2) - (c_0 + c_1 Q_m)$$

Where;

$Cost(Q_m) = c_0 + c_1 Q_m$

An EPANET pipeline simulation model was used to determine the power, pumping capacity and the average daily pumping cost given the length, diameter and elevation of the pipelines. Water demand data for each of the twelve months for the year 2010 through 2050 were used in this simulation model. The simulation model estimated the costs of capital investment in pipelines and water treatment facilities based on the population level of different years from 2010 through 2050. The EPANET2 software was used to run this simulation model while the pipeline files, district boundary files, facility files were obtained from the Oklahoma Water Resources Board (OWRB). Given the variable energy cost of pumping (obtained from the simulation model) a linear cost function was estimated as:

$$Cost_m = -458 + \underset{(2.5)}{}\underset{(760)}{257.64}Qd_m \qquad R^2 = 0.99$$

* t-values were in parenthesis

Where,

$Cost_m$ = total pumping cost in month m

Qd_m =amount of water pumped (or demanded) in month m (acre feet)

The variable cost was the dollar value of the total pumping cost of Q_m acre feet of water for the entire system in a particular month. For this study only the variable cost (i.e. the marginal delivery cost) was considered even though the final delivery price includes the cost of amortizing the system and also the local distribution costs of each system (fixed cost).

An outline of the proposed pipeline map was shown in Figure IV-4 below. The map had been overlaid on a USGS 1/3 second elevation file for the region. The pipelines would serve communities around the lake along with the town of Gore and Vian to the south. The pipeline also partially served the city of Tahlequah and other rural water districts to the north.

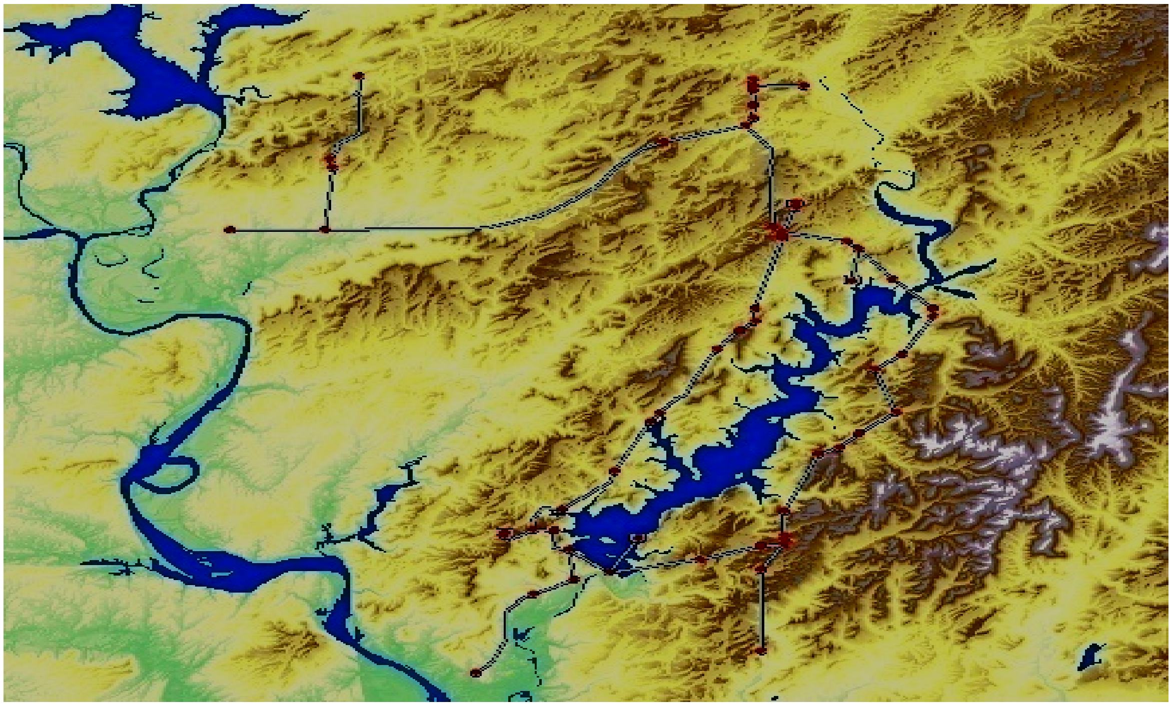

Figure IV-4 Pipeline Serving Rural Water System Of Lake Tenkiller Surrounding Area
Source: OWRB

Table IV-5 Monthly Water Demand By The Lake Tenkiller Surrounding Area, Fixed Supply Cost And The Price Necessary To Reduce Consumption By One Unit.

Month	Base Quantity Demand (Ac Ft)	Base Price Of 1 Ac Ft (US $)	Price Necessary To Reduce Consumption By 1 Ac Ft (US $)
Jan	840.70	$ 257.64	$ 726.97
Feb	721.94	$ 257.64	$ 728.41
Mar	762.64	$ 257.64	$ 426.32
Apr	726.86	$ 257.64	$ 738.44
May	814.98	$ 257.64	$ 713.93
Jun	870.37	$ 257.64	$ 714.14
Jul	1,084.01	$ 257.64	$ 713.60
Aug	1,087.61	$ 257.64	$713.60
Sep	944.44	$ 257.64	$ 714.07
Oct	896.53	$ 257.64	$ 725.70
Nov	796.72	$ 257.64	$ 727.54
Dec	796.35	$ 257.64	$ 727.76

In the Table IV-5, the monthly water demand, the variable pumping cost (supply cost) and the price necessary to incurred in order to reduce the consumption by one acre feet were shown. This price was the marginal value of rural and urban water use when the consumption was decreased by one acre foot.

It was already mentioned that GAMS required simple equations and proper scaling, thus grid linearization technique (Duloy and Norton, 1975) was used to linearize the quadratic NSB water consumption function. The total welfare for each month was calculated by using the NSB equation for that particular month and in the programming model it was allowed to move within a given range, while a convexity condition was added as a constraint for each month assuming a perfectly elastic supply function of water at the marginal pumping cost of $257.64 per acre foot.

Estimation of Lake Recreational Benefit

In this research study, it was assumed that the monthly lake visitation depends on the lake level for that particular period of time and the visitation should be maximized when the lake level was around the normal lake level. According to the US Army Corps of Engineers website, for Lake Tenkiller the normal lake level was around 632 feet.

Visitation data from the period of 2001 through 2007 were obtained from USACE website. Six years data were not enough to estimate the lake visitation. Thus, secondary data over the period of 1955 through 1974 published by Badger and Harper (1975) were also used for this study.

The effect of differnet lake levels on the visitor attendance was estimated by regressing the number of monthly visitors (from 1955 to 1974 and from 2000 through 2004) against the lake level for the same period. The estimated regression equation used in this study was as follows:

$$\begin{array}{lllll} \text{Visits} = 103733 + 83400\text{Apr} & + 182031\text{May}^* & + 337142\text{June} & + 401425\text{July}^* + & \\ \qquad\qquad\qquad (4.46) & \quad 9.57) & \quad (13.26) & \quad (15.31) & \end{array}$$

$$\begin{array}{llllll} 316164\ \text{Aug} & + 117626\ \text{Sep}^* & + 2642\text{ALkLv}^* & + 5227\text{LvJun}^* & + 2654\text{Tsumr}^* \\ (12.97) & \quad (6.32) & \quad (3.28) & \quad (1.57) & \quad (4.30) \end{array}$$

$$\begin{array}{lll} - 254\ \text{Lv}_{\text{Jn}}^{2*} & - 1072\text{Lv}_{\text{Jly}}^{2*} & - 254\ \text{Lv}_{\text{Aug}}^{2*}, \\ (-1.95) & \quad (-2.51) & \quad (-1.95) \end{array}$$

$R^2 = 0.66$ and t-values were in parentheses

- The variables Apr, May, June, July, Aug and Sep were 0-1 dummy variables which were 1 in the indicated months and zero otherwise.
- Tsumr was a time trend for months June, July, and August. The other months were not found to significantly vary with time.
- ALkLv was the average monthly lake level – 632 (normal lake level).
- LvJun was a discrete variable to test if visits to the lake in June were more sensitive to lake levels than in other months.
- Lv_{Jn}^2 was the square of the June lake level – 632 (normal lake level),
- Lv_{Jly}^2 was the square of the July (lake level – 632(normal lake level), and
- Lv_{Aug}^2 was the square of the August (lake level – 632(normal lake level).

Using the above regression equation, the visitors' day at a normal lake level of 632 feet for the year 2010 was predicted and represented in the following figure.

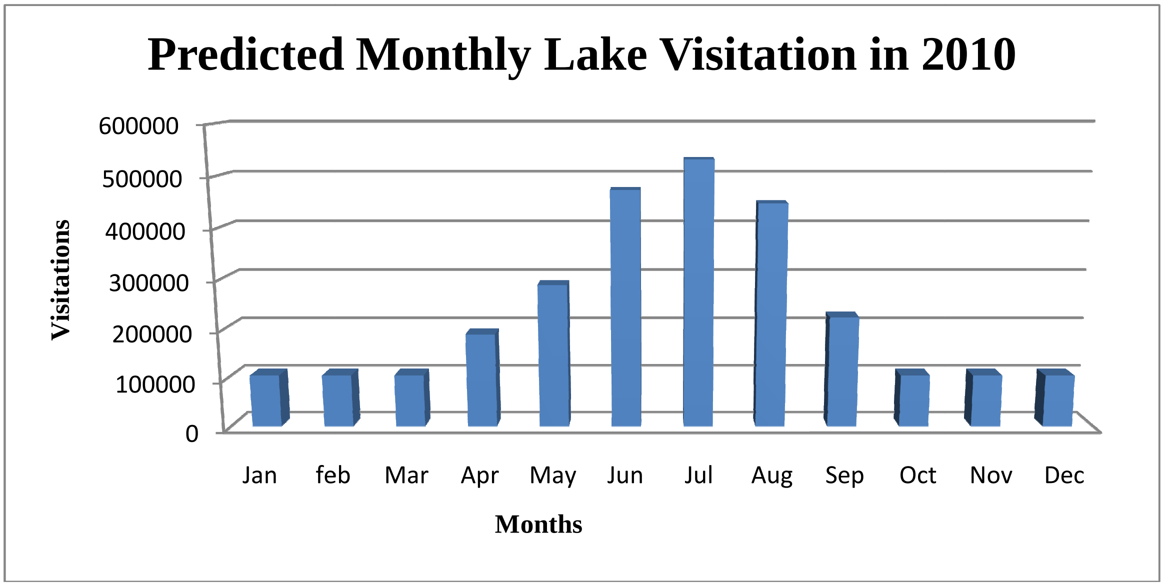

Figure IV-5 Estimated Visitor Days For The Year 2010 At The Normal Lake Level Of 632

The recreational value of Lake Tenkiller was estimated as part of a larger random utility travel cost model for all lakes in Oklahoma (Boyer, 2008). The value of a visitor day to Lake Tenkiller, Lake Fort Gibson, and Bell Cow Lake were estimated to be $191, $136, and $22 per day respectively. In this study, the value of a visitor day at the normal lake level was placed at only $50 per day. This was a conservative value, well below the estimated value of $191 per day. The study by Roberts et al. (2008) had shown that the willingness to pay for a visitor day declined by $0.82 for each foot the lake was below the normal level. Their study was based on the random utility model, where individuals random utility derived from visiting the lake was based on lake water level, individuals' cost incur to visit the lake, and the presence of algal bloom (takes 1 when there was bloom and 0 otherwise). They also treated lake level as stochastic since rainfall were stochastic and found that people were willing to pay more for the normal lake level and their willingness to pay decreased till it reached 8 feet below the normal lake level. For Lake Tenkiller, the normal lake level was 632 feet (based on USACE normal pool level) and value of visitors' day decreased till it reach the level of 624 feet based on Robert et al (2008) study. Thus, the value of a visitor day used in this model was taken to be:

$50 per day if the lake level ≥ 632 feet,

$43 + $0.82*(Lake Level – 624) if the lake level is > 624 and < 632,

$43 per day if the lake level is ≤ 624 feet

The recreational value used in this study was shown in following figure:

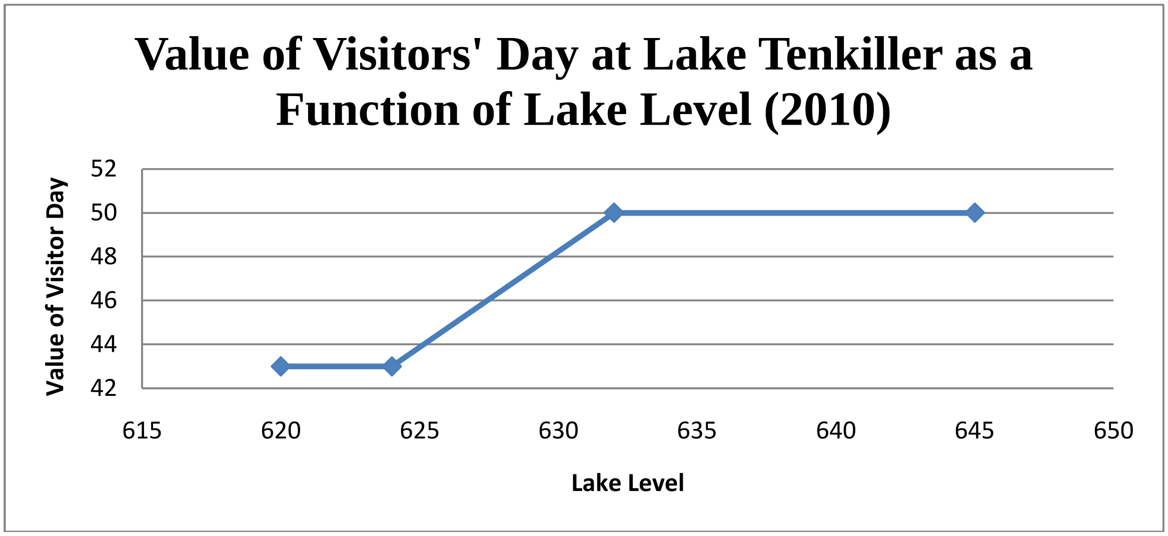

Figure IV-6 Value Of Visitors Day Depending On The Lake Level

In the GAMS model, initially the lake level - volume relationship was used to convert the ending volume of each month of reservoir water into lake level and then the monthly lake level was used to calculate the visitation of each month. A *min* function was used to calculate the visitation of the winter months from October through March that would fix the winter visitation irrespective of the lake level. During the summer months from April through September the lake visitation was sensitive to the lake level. In order to keep the lake level around the normal lake level of 632 feet during the summer months, again a *min* function was used in GAMS.

Finally, the economic benefits arising from lake recreation were determined by multiplying the estimated number of visits in each month to the value of a visitor day at a given lake level (mentioned above). This was represented as:

$$BR_m = Val_m * V_m$$

Where BR_m : Lake Recreational Benefits in month *m*

Val_m : Value of visitor day at a given lake level in month *m*

V_m: Total number of visits in month *m*

CHAPTER V

RESULTS AND DISCUSSION

Several management strategies were considered while allocating Lake Tenkiller water among different uses. The model was solved for the year 2010, assuming that the population of the surrounding area of Lake Tenkiller will not be varied too much from that of 2009 (June) and the monthly price of electricity was also same as of 2008. It was found that when the model (with recreational values in the objective function) was solved based on the average monthly historical inflows, outflows and lake volume data, the total benefits were around $217,947,806, while there was a total benefits of $230,722,322 when the optimization model (with recreational values in the objective function) endogenously determined the monthly outflows for each sectors and the average monthly lake volume. Thus, in the optimization model by controlling the monthly water releases for hydropower generation, urban and rural water uses and other releases and maintaining a normal lake level of 632 FASL during the summer months of June, July and August there was around 5.86% increase in the total benefits. Both, the hydroelectric power generation benefits and lake recreational benefits were increased by $1.8 million and $3.5 million respectively while the urban and rural water supply benefits remained same.

The average historical monthly lake level was compared with the derived optimal operating levels that would maximize the total benefits arising from hydroelectric power generation, lake recreation and urban and rural water supply when recreational benefits were and were not included in the objective function .This was shown in the following figure.

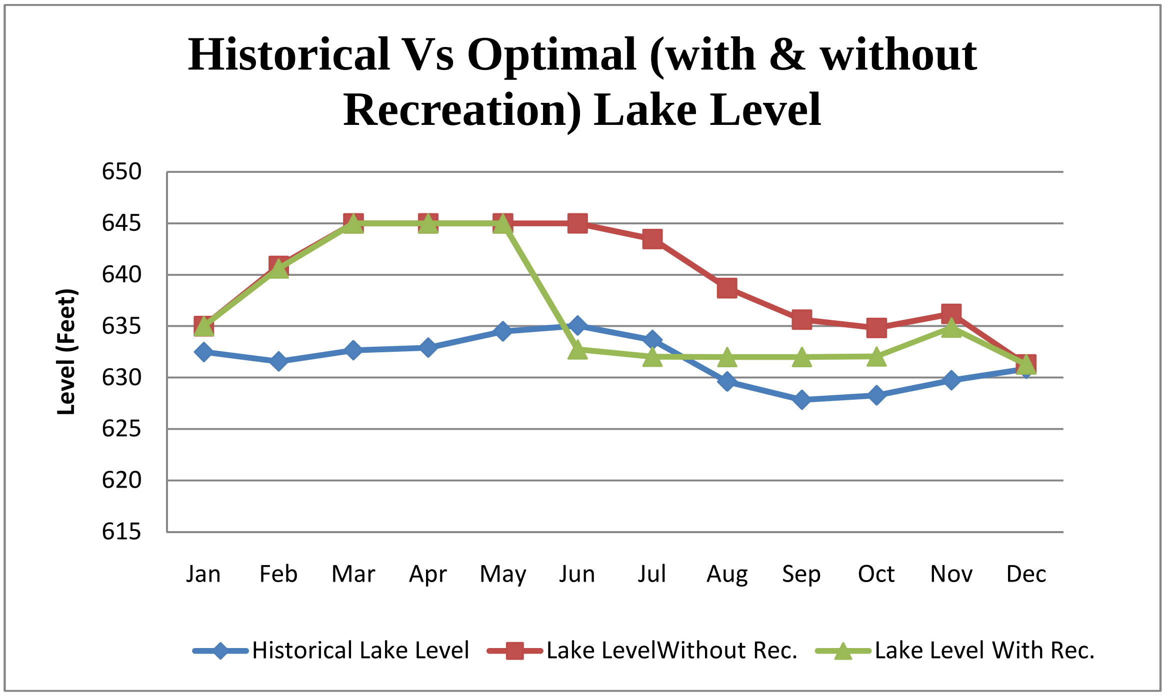

Figure V-1 Comparison Of Average Historical Monthly Lake Level For Lake Tenkiller From 1990-2006 With The Optimal Lake Level For 2010 When Recreational Values Were And Were Not Included In The Optimization Model

In Figure V-1, the average monthly historical lake levels from 1990 through 2006 were compared with the derived optimal lake levels when recreational values were and were not included in the objective function. The Figure V-1, showed that US Army Corps of Engineer (USACE) were currently maintaining the lake level around (5-feet below or above) the normal pool of 632 feet. However, if the lake was managed to maximize both the hydropower and recreational benefits, it was always beneficial to maintain a lake level of around the normal lake level of 632 feet during the summer months of June, July and August respectively. Since, any lake level above and below the normal lake level of 632 feet would definitely reduce the visitation for those months, and it was shown latter in this study. By contrast in the model where hydroelectric power generation benefits were the main concerned of the management (i.e. lake recreational benefits were not included in the objective function) then it would be beneficial to increase the lake level for maximum head above the turbine and release water during the summer months when the electricity price was at peak.

Results

The model was solved considering different management scenarios. First, when the lake recreational benefits were considered within the optimization model and secondly when the recreational benefits were not considered in the objective function. The results of these two strategies were compared in the following table:

Table V-1 Comparison Of Total Benefits Arising For Lake Tenkiller When Recreational Values Were And Were Not Included In The Objective Function For Year 2010

Recreational Values in Obj Fun.			Recreational Values not in Obj Fun.		
Recreation	$	138,280,000	Recreation	$	128,520,000
Hydropower		7,928,700	Hydropower		8,108,500
Rural Water Supply (RWS)		84,518,000	Rural Water Supply (RWS)		84,518,000
Total Benefit $ (with recreation in Obj fun)		230,726,700	Total Benefit $ (without recreation in Obj fun)		221,146,500

*Recreation valued at $50 per day

When recreational benefits were directly included in the objective function, there was an additional annual gain of nearly $9,580,200 to the lake resource values which was around 4.3%. In this study, the recreational visitor days were valued at $50 per visitor day and by including the recreational values into the optimization model the benefit arising from the recreational use was increased by $9,760,000. Thus, there was around 7.6% gain in the recreational benefits by including recreational benefits in the objective function. The hydroelectric power generation benefits were decreased by $179,700, when the recreational benefits were included in the objective function. While the benefit arising from the urban and rural water supply uses remained same in both cases, mainly due to the fact that the model was solved only for a particular year (2010) with a fixed number of populations and the urban and rural water supply function was considered as perfectly elastic.

This tradeoff between lake recreational benefits and hydroelectric power generation benefits when recreational benefits were included in the objective function was shown in the following bar diagram.

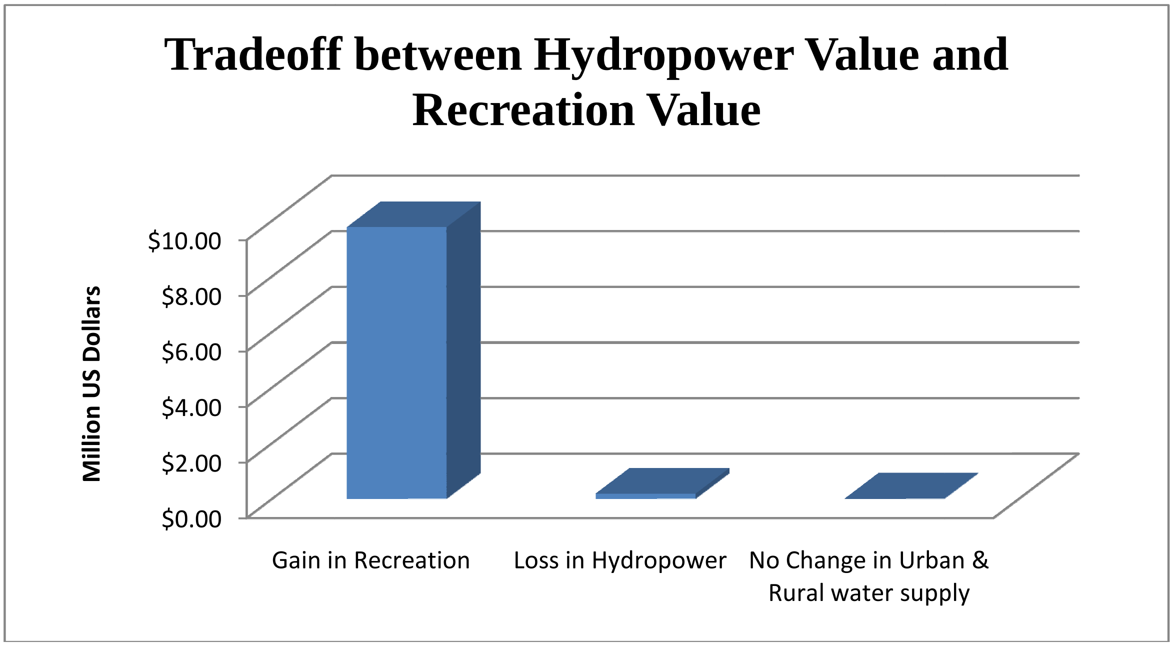

Figure V-2 Comparison Between The Loss In Hydroelectric Power Generation Values Vs Gain In Lake Recreational Values When Recreational Values Were Included In The Objective Function For Year 2010

The Figure V-2, showed that when the recreational benefits were included in the objective function i.e. private as well as social benefits arising from the use of Lake Tenkiller water were considered, then there was an additional gain of around $9,760,000 from recreational benefits for the year 2010, and a loss of around $179,700 in hydroelectric power generation benefits mainly due to maintaining the normal pool of 632 feet during the summer months, while the benefits derived from urban and rural water use was same since the urban and rural water supply use over a particular year was always same. It was always beneficial to include the recreational benefits in the objective function while managing Lake Tenkiller, since the additional recreational gain was around 54 times of the loss incurred due to the reduction in hydroelectric power generation value. Thus, while managing Lake Tenkiller considering only the marketed values such as hydroelectric power generation and urban and rural water supply uses (recreational benefits was not included in the objective function) it reduced the total benefits by $179,700. But, if the objective of managing Lake Tenkiller was to maximize the marketed as well as the non-marketed benefits then the recreational benefits should be included in the objective function.

The lake volume, outflows, and the releases pattern for the optimization model when the recreational benefits were included in the objective function were as follows:

Table V-2 Lake Tenkiller Monthly Lake Volume, Level, And Releases That Maximizes The Total Benefit With Recreation Benefit In The Objective Function

Month	Ending Lake Level (Feet)	Beginning Volume (Acr. Feet)	Hydropower Release (Acr. Feet)	Water Supply Release (Acr. Feet)	Other Use Release (Acr. Feet)
Jan	635.00	644,640	84,437	841	-
Feb	640.86	693,380	17,443	722	-
Mar	645.00	775,630	64,541	763	-
Apr	645.00	838,750	137,390	727	-
May	645.00	838,750	124,380	815	-
Jun	632.73	838,750	291,930	870	-
Jul	632.03	663,390	61,172	1,084	-
Aug	632.00	654,330	19,520	1,088	-
Sep	632.00	653,920	25,368	944	-
Oct	632.05	653,910	31,618	897	-
Nov	634.87	654,500	48,107	797	-
Dec	631.28	691,610	134,750	796	-

During the summer months, mainly of June, July and August, when the lake visitation was at its peak the lake level should be maintained at around the normal lake level of 632 feet and the releases for hydroelectric power generation and the other releases for in-stream recreational uses should be adjusted accordingly.

For this study, Lake Tenkiller was considered which was a part of a big electricity generating system. Thus, it was assumed that any amount of electricity generated was sold at the spot market. But, if Lake Tenkiller was operated individually then the total amount of electricity produced in a particular month was not completely sold. Table V-2, showed that there were no other releases through the gate for in-stream uses; since it was always beneficial to release water through the turbine as it simultaneously generates some revenue from hydroelectric power generation and also meet the in-stream recreational uses. Thus, for Lake Tenkiller water should be released through the turbine as long as the release was within the maximum capacity of the generator

The total annual visits for the year 2010 were more when the recreational benefits were included in the objective function, than the case when the recreational benefits were not included in the objective function. The comparisons between these two management scenarios were shown in the Table V-3:

Table V-3 Comparison Between Monthly Visitation For Lake Tenkiller When Recreational Benefits Were And Were Not Included In The Objective Function And Their Difference

Month	Visitation with Recreation	Visitation without Recreation	Difference in Visitation between with & without Recreation
Jan	103,730	103,730	0
Feb	103,730	103,730	0
Mar	103,730	103,730	0
Apr	187,170	187,170	0
May	285,800	285,800	0
Jun	472,510	429,720	42,790
Jul	531,700	390,840	140,860
Aug	446,440	435,050	11,390
Sep	221,400	221,400	0
Oct	103,730	103,730	0
Nov	103,730	103,730	0
Dec	101,830	101,830	0
Total	2,765,500	2,570,460	195,040

The Table V-3 showed that during the summer months of June through August the number of visitors were more when the recreational benefits were included in the objective function. For the year 2010, there would be an annual increase in the number of visitors when the recreational benefits were included in the objective function compare to the case when recreational benefits were not included in the objective function. It was expected that when recreational benefits were included in the objective function there would be 193,920 more visitors. In case of Lake Tenkiller for the year 2010 in the month of July only there would be 140,860 more visitors, if the lake was managed considering both the marketed (hydropower generation values and urban and rural water use values) and the non-marketed (recreational values) uses.

It was earlier mentioned that for Lake Tenkiller, monthly lake visits were sensitive to the lake level when recreational benefits were included in the objective function. It was shown in the Figure V-3.

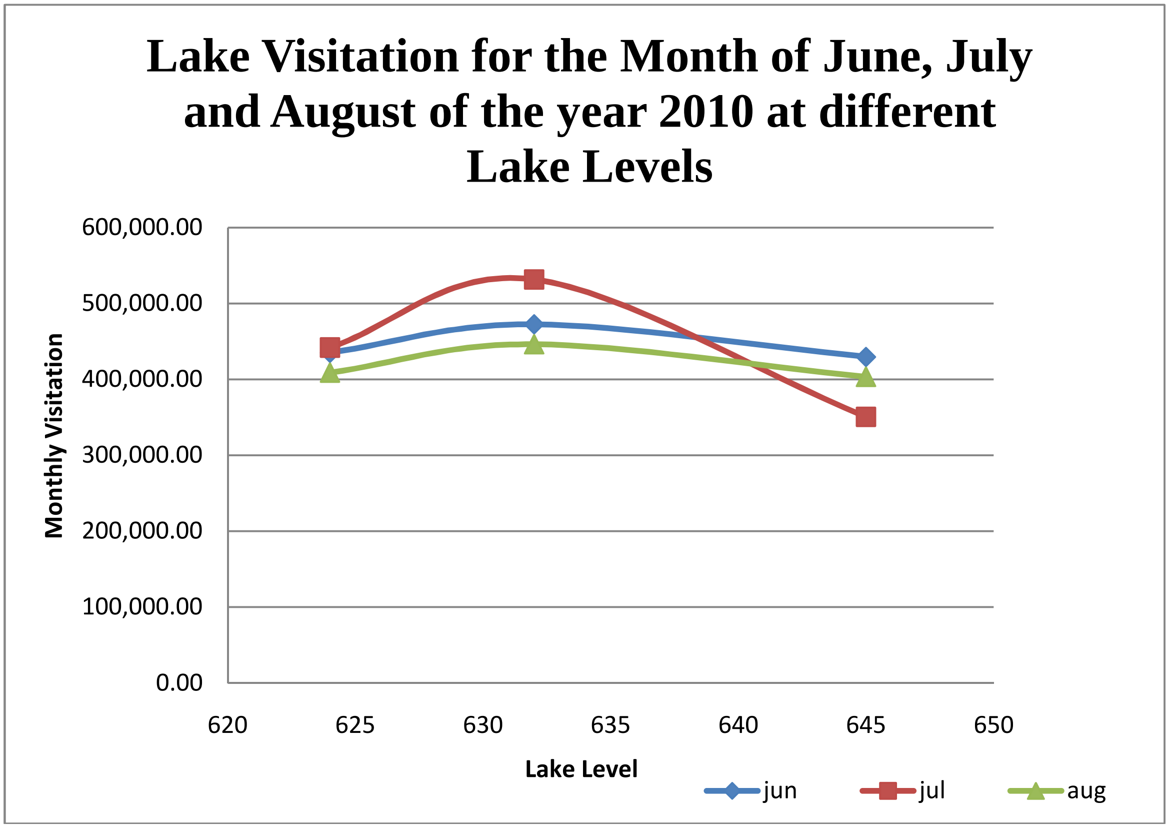

Figure V-3 Number Of Visits For Lake Tenkiller At Different Lake Levels For The Month Of June, July And August Of Year 2010

The above Figure V-3, showed that for Lake Tenkiller at the normal lake level of 632 feet the monthly number of visits was maximum and at any lake level below and above the normal pool of 632 feet the monthly lake visitation had decreased. Therefore, the lake visits were sensitive to the lake level above and below the normal lake level.

The number of visitors for each month for Lake Tenkiller obtained from the optimization model when the recreational benefits were and were not included in the objective function was compared with the average historical visitation in Figure V-3.

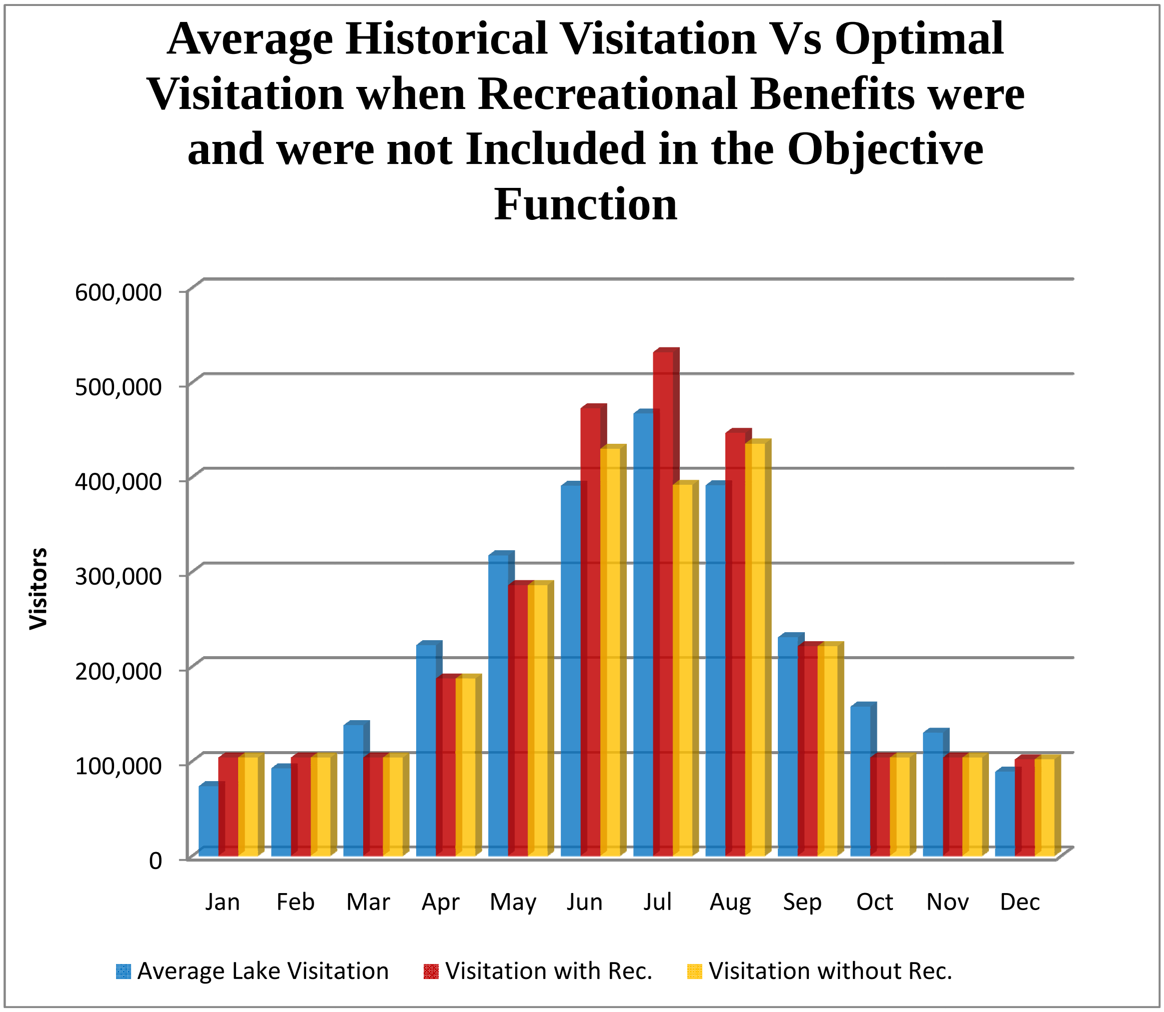

Figure V-4 Comparison Of The Optimal Number Of Monthly Visitation For Lake Tenkiller When Recreational Benefits Were And Were Not Included In The Objective Function With The Average Monthly Historical Visitation

Figure V-4, showed that for Lake Tenkiller for the year 2010 the numbers of visitors were maximized during the summer months of June, July and August when the visitation was at its peak and when the recreational benefits were included in the objective function then the number of visitors during the summer months of June, July and August were maximum. For Lake Tenkiller, it was found that the average number of visitors (from the year 2000 through 2007) and the number of visitors obtained from the optimization model when recreational values were and were not included in the objective function were at its peak during the summer months of June, July and August respectively.

In the case of hydroelectric power production, the situation was reversed; less hydropower was generated when recreational benefits were included in the objective function compared to the case when recreational benefits were not included in the objective function. This was shown in the following table:

Table V-4 Comparison Between The Amount Of Hydropower Generation In Each Month When Recreational Benefit Were And Were Not Included In The Objective Function

Month	Hydropower Production With Recreation In MWH*	Hydropower Production Without Recreation In MWH*	Difference Between W Hydropower Production Without And With Recreation In MWH*
Jan	6,954.80	6,954.80	0.00
Feb	1,500.00	1,500.00	0.00
Mar	5,715.77	5,715.77	0.00
Apr	12,167.49	12,167.49	0.00
May	11,014.88	11,014.88	0.00
Jun	23,635.48	10,323.01	-13,312.47
Jul	4,926.13	6,668.69	1,742.56
Aug	1,570.54	7,573.88	6,003.34
Sep	2,042.41	5,608.30	3,565.89
Oct	2,546.48	3,553.37	1,006.89
Nov	3,958.49	5,549.15	1,590.66
Dec	10,788.19	12,214.61	1,426.42
Total	86,820.66	88,843.95	2,023.29

**MWH Megawatt Hour*

The total amount of electricity produced throughout the year (2010) was 86,820.66 MWH when recreation values were included in the objective function while 88,843.95 MWH of electricity were produced when recreational values were not included in the objective function. The hydropower production was decreased by 2,023.29 MWH, when recreational values were included in the objective function. Table V- 4, showed that when the recreational benefits were included in the objective function, the maximum amount of electricity was produced in the month of June. A huge amount of water was released through the turbine in the month of June in order to maintain the normal lake level of 632 feet during the summer months of June, July and August that would maximize the recreational benefits. While during the month of June, the in-stream recreational benefits (mainly arising from trout fishing) might lose some value due to a huge amount of water released for hydropower generation in that particular month and in the case, when recreational benefits were not included in the objective function, i.e. the reservoir was only managed for maximizing hydropower generation benefits then more often electricity was produced throughout the year depending on the inflows to the reservoir.

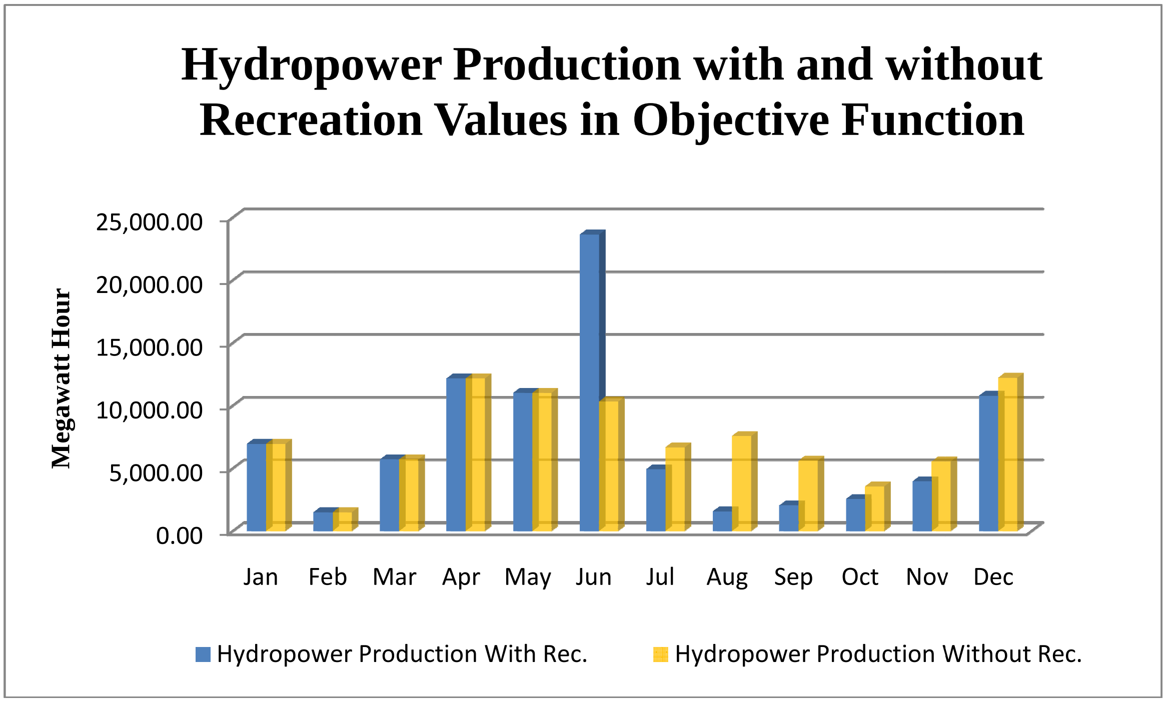

Figure V-5 Comparison Of Optimal Amount Of Hydropower Production For Lake Tenkiller When Recreational Benefits Were And Were Not Included In The Objective Function

In Figure V- 5, it was shown that when recreational benefit were included in the objective function then less amount of electricity was produced during the months from July through December than when recreational benefits were not explicitly included in the objective function.

The urban and rural water use demand (in acre feet) by the surrounding area of Lake Tenkiller was same for both the cases, since for both cases the population of that area was constant and the supply function for water was elastic. The monthly water demand, welfare derived from that water demand and the corresponding price were shown in Table V-5:

Table V-5 Monthly Urban And Rural Water Demand By The Surrounding Area Of Lake Tenkiller, Welfare Derived From That Particular Water Demand And The Price Obtained From The Price Flexibility Form Based On That Water Demand

Month	Urban & Rural Water Demand (Acre Feet)	Welfare Derived From The Water Use (In US $)	Price Of Water (In US $)
Jan	841.00	$11,090,494.07	$967.54
Feb	722.00	$9,523,728.72	$974.52
Mar	763.00	$10,062,104.47	$968.11
Apr	727.00	$9,588,959.16	$972.53
May	815.00	$2,387,950.00	$974.00
Jun	870.00	$2,551,579.50	$979.70
Jul	1,084.00	$3,175,447.92	$972.76
Aug	1,088.00	$3,191,147.52	$980.08
Sep	944.00	$2,767,732.48	$977.84
Oct	897.00	$11,827,281.38	$963.75
Nov	797.00	$10,511,625.03	$970.98
Dec	796.00	$10,504,302.56	$985.72
Total	**10,344.00**	**$87,182,352.80**	**$11,687.53**

The Table V-5 showed that during the summer months of June through September, the urban and rural water demand was at its peak. This was mainly because during the summer months, the water consumption was more due to watering of the lawn and many other uses. While the welfare associated with that (summer months) water use were less compared to the other months. The price was obtained from the inverse demand function (price flexibility form) at a particular (monthly) water demand based on the monthly slope and intercept coefficients shown in the sixth and seventh column of Table-IV-4. It didn't include the treatment and delivery cost which was $257.64 per acre foot.

In the final or optimal solution, the marginal value or shadow price of water in each alternative use must be equal when measured at the lake. Table V-6 shows that the marginal cost of treatment and delivering an acre foot of water (column 2) less the cost of treatment and delivery (column 3) is equal to the VMP (Price of 1 Acre Foot of water at the Lake) of water at the lake (column 4)

Table V-6 Actual Cost, Supply (Pumping) Cost Of One Acre Foot Of Water For Urban And Rural Water Supply Use To The Surrounding Area Of Lake Tenkiller, And Per Unit (Acre Foot) Price Of Water At The Lake For Each Month

Month	Actual Cost of 1 Acre Foot of water[a,b]	Supply Cost of 1 Acre Foot of water[a]	Price of 1 Acre Foot of water at the Lake(VMP)[a]
Jan	$264.97	$257.64	$7.33
Feb	$265.29	$257.64	$7.65
Mar	$265.52	$257.64	$7.88
Apr	$265.52	$257.64	$7.88
May	$265.65	$257.64	$8.01
Jun	$265.30	$257.64	$7.66
Jul	$265.42	$257.64	$7.78
Aug	$265.42	$257.64	$7.78
Sep	$265.22	$257.64	$7.58
Oct	$264.98	$257.64	$7.34
Nov	$264.88	$257.64	$7.24
Dec	$264.68	$257.64	$7.04

[a] in US $ per acre feet

[b] column 2 is equal to column 3 + column 4

Table V-6, showed that the marginal price of water delivered for urban and rural water supply use (obtained from the GAMS output) was higher by the amount of treatment and delivery cost to the area surrounding Lake Tenkiller. This was because the users were usually charging only the delivery and treatment cost but not the cost of holding water for alternative uses, thus consumer received water at a subsidized rate. The price difference between the true delivered marginal cost of water and cost of treatment and delivery of one acre foot of water was the opportunity cost of water at the lake. Column (4) of Table IV-5 showed the price necessary to reduce consumption by one acre foot which was way above the marginal (shadow) price of water obtained from the optimization model shown in column (5) of Table V-6.

Table V-7 Monthly Hydroelectric Power Generation Benefits, Amount Of Water Released For Hydroelectric Power Generation And The Value Of Hydropower Generated Per Acre Foot Of Water Released

Month	Total Hydropower Generation Benefits[a]	Hydropower Releases (Acre. Feet)	Value of Hydropower Generated Per Acre Foot of Water Released[a,b]
Jan	$618,980	84,437	$7.33
Feb	$133,500	17,443	$7.65
Mar	$508,700	64,541	$7.88
Apr	$1,082,900	137,390	$7.88
May	$996,850	124,380	$8.01
Jun	$2,238,300	291,930	$7.67
Jul	$475,860	61,172	$7.78
Aug	$151,560	19,508	$7.77
Sep	$192,190	25,369	$7.58
Oct	$232,190	31,619	$7.34
Nov	$348,350	48,107	$7.24
Dec	$949,360	134,750	$7.05

[a] in US $

b Column (4) is equal to Column (2) divided by Column (3)

In Table V-7, the average and marginal price of water at the lake was obtained by dividing the total benefits derived from hydropower generation uses by the total amount of water releases in each month from the lake for this purpose. Since, in this study hydroelectric power generation was considered as a linear function of the amount of water released for this purpose. Thus, the marginal product derived from the hydropower use equates the average product for the same use (first derivative of linear function was its' average function). Comparing Table V-6 and Table V-7, it was found that the price of water at the lake for both hydroelectric power generation and urban and rural water use are same.

Thus, for Lake Tenkiller the equi-marginal principle hold while allocating reservoir water among the marketed uses (a) hydroelectric power generation use and (b) urban and rural water supply use. That is, it was not possible to take one additional acre foot of water from hydropower generation use and transfer it to urban and rural water supply use and increase the total benefits arising from the marketed uses of the Lake Tenkiller.

The following table represents the amount of hydropower produced in each particular month and its corresponding benefits and the marginal (shadow price) cost of electricity for that particular month when recreational values were included in the objective of the optimization model, amount of water released for hydropower generation and the value of hydropower generated per acre foot of water released.

Table V-8 Monthly Hydropower Production, Hydroelectric Power Generation Benefit And Shadow Price For Hydropower Production Obtained From The Optimization Model When Recreation Values Were Included In The Objective. Function

Month	Hydropower Production With Recreation (1000 Kwh)	Hydropower Production Benefit (US $)	Shadow Price For Per 1000 Kwh Of Hydropower Production (US $)[a]	Hydropower Releases (Acre. Feet)	Value Of Hydropower Generated Per Acre Foot Of Water Released[b]
Jan	6,954.80	$618,980	$ 89.00	84,437	$7.33
Feb	1,500.00	$133,500	$ 92.44	17,443	$7.65
Mar	5,715.77	$508,700	$ 89.00	64,541	$7.88
Apr	12,167.49	$1,082,900	$ 89.00	137,390	$7.88
May	11,014.88	$996,850	$ 90.50	124,380	$8.01
Jun	23,635.48	$2,238,300	$ 94.70	291,930	$7.67
Jul	4,926.13	$475,860	$ 96.60	61,172	$7.78
Aug	1,570.54	$151,560	$ 96.50	19,508	$7.77
Sep	2,042.41	$192,190	$ 94.10	25,369	$7.58
Oct	2,546.13	$232,190	$ 91.18	31,619	$7.34
Nov	3,958.49	$348,350	$ 88.00	48,107	$7.24
Dec	10,788.19	$949,360	$ 88.00	134,750	$7.05

Shadow Price: the extra amount of cost incurred in order to produce one additional unit of hydropower

[a] Column (4) is equal to Column (3) divided by Column (2), b Column (6) is equal to Column (3) divided by Column (5)

Table V-8, showed that the benefits derived from hydropower generation were maximized in the month of June when the highest amount of electricity was produced. The benefits derived from hydroelectric power generation depend on the amount of electricity produced on that particular month. The marginal price of hydroelectricity was at its peak during the summer months of June through September when the electricity demand was also at its peak.

The final step was to show that at the different lake levels during the summer months of June, July and August the equi-marginal principle held while allocating Lake Tenkiller water between recreational, hydroelectric power generation and municipal uses. This was more difficult for recreational uses because recreation values depend on the lake level and it was maximized only when the lake level was at its normal pool of 632 feet. In order to illustrate how the marginal benefits derived from hydropower generation and recreational use changes relative to each other, the marginal benefits for those two uses were calculated by lowering each foot of the lake level from 645 feet to 627 feet. It is shown is Table V-9. The regression equation on page 37 and the Figure V-3, indicate that the peak visitation occurred only when the lake level was around 632 feet.

Table V-9 Lake Levels, Corresponding Volume Hydropower And Recreation Benefits For The Volume Of Water, Value Of Marginal Product (VMP) For Hydropower Generation Use And Recreational Use For The Month Of June Derived From The Use Of Lake Tenkiller Water And The Total Gain Or Loss Derived From 1 Acre Foot Of Water Use At Different Lake Level

Level (Feet)	Volume (Acre Feet)	Hydropower Benefit (Per Acre Foot)	VMP-Hydropower Generation Use (Per Acre Foot)[a]	Recreational Benefit (Per Acre Foot)	VMP-Recreational Use (Per Acre Foot)[b]	Total Gain/Loss (Per Acre Foot)[c]
645-644	15,695	$123,702	$7.88	$317,500	$20.23	$28.11
644-643	15,401	$120,539	$7.83	$292,000	$18.96	$26.79
643-642	15,123	$117,530	$7.77	$266,500	$17.62	$25.39
642-641	14,860	$114,664	$7.72	$241,500	$16.25	$23.97
641-640	14,609	$111,928	$7.66	$216,000	$14.78	$22.45
640-639	14,372	$109,313	$7.61	$190,500	$13.26	$20.86
639-638	14,145	$106,809	$7.55	$165,000	$11.67	$19.22
638-637	13,928	$104,407	$7.50	$139,500	$10.02	$17.51
637-636	13,722	$102,102	$7.44	$114,500	$8.34	$15.79
636-635	13,524	$99,885	$7.39	$89,000	$6.58	$13.97
635-634	13,335	$97,751	$7.33	$63,500	$4.76	$12.09
634-633	13,153	$95,695	$7.28	$38,000	$2.89	$10.16
633-632	12,979	$93,711	$7.22	$12,500	$0.96	$8.18
632-631	12,811	$91,794	$7.17	-$529,695	-$41.35	-$34.18
631-630	12,650	$89,940	$7.11	-$550,103	-$43.49	-$36.38
630-629	12,494	$88,146	$7.06	-$568,280	-$45.48	-$38.43
629-628	12,344	$86,409	$7.00	-$585,695	-$47.45	-$40.45
628-627	12,200	$84,727	$6.94	-$601,855	-$49.33	-$42.39

[a] Column (4) is equal to Column (3) divided by Column (2), [b] Column (6) is equal to Column (5) divided by Column (2),
[c] Column (7) is equal to Column (4) + Column (6)

The values in Column (2), (3), (4), (5), (6) and (7) of Table V-9 were derived by successively lowering the lake level from 645 feet to 627 feet above the sea level. Table V- 9 showed the marginal value of one acre foot of water at different lake levels for both market (hydroelectric power generation and urban and rural water supply) and non-market (recreational) uses. The Column (2) of Table V- 9 showed the volume of water per foot above sea level at different lake levels While, Column (3) and Column (5) represents hydropower and recreational benefits for the different lake levels and its corresponding lake volume. The Value of Marginal Product (VMP) of hydropower generation and recreational use were derived by dividing the benefits occurred from that particular use per foot of water by the volume of water per foot above sea level at different lake levels. It was shown in Column (5) and (6) respectively.

The Value of Marginal Product (VMP) derived from hydropower generation and recreation use followed the same trend as the lake level was lowered from 645 to 632 feet (where recreational use was at its maximum) and as the lake level was reduced further recreational use declines and the total benefit derived from recreational use decreased. While the VMP-Hydropower Generation uses also decreased along with the lake level as expected. With lower lake level the elevation of the reservoir declined and consequently the VMP of hydropower generation reduced. It was also found that for any lake level below the normal lake level of 632 feet, there was a total loss in the VMPs'. Thus, for Lake Tenkiller it was always beneficial to maintain a normal lake level of 632 feet during the summer months when the recreational benefits were at their maximum. It was shown in Figure V- 3.

It was already shown in Table V- 3, that for Lake Tenkiller the maximum number of visitors were during the summer months of June, July and August when the lake level was around the normal pool of 632 feet. Therefore, the corresponding recreational benefits were maximized during that period of a particular year. Thus, during the summer months the recreational gain was much more by maintaining the normal lake level of 632 than the loss incurred not by releasing additional acre foot of water for hydroelectric power generation. This tradeoff was shown in the following table.

Table V-10 Estimation Of The Tradeoff Between Recreational Benefits And Hydropower Production Benefits By Lowering The Lake Level From 632 To 631 Feet During The Summer Months

Gain in Hydropower Generation Benefits from Additional Releases by Reducing the Lake Level by 1 foot

Lake Level (feet)*	Volume (in 1000 acr ft)	Release (in 1000 acr ft)	Hydropower generation (in 1000 Kwh)	Hydropower Benefit ($1000)
632	654	13	440	42
631	641			

Loss in Recreational Benefits by Reducing the Lake Level by 1 Foot during the Summer Months

Month	Level	Estimated Visits (1000)	Recreation Benefit ($1000)	Loss ($ 1000)
May	632	286	14,288	364
	631	283	13,924	
Jun	632	473	23,632	531
	631	470	23,101	
July	632	532	26,585	619
	631	528	25,966	
August	632	446	22,322	509
	631	444	21,813	

*feet above sea level

In Table V-10, the summer month's recreational loss if the lake level was reduced by one foot was compared with the hydropower generation gain due to an additional acre foot of water released for that purpose. While calculating the hydropower generation benefits derived from one foot of water released, the price of electricity was considered as

9.5 cents per kilowatt hour (summer months' electricity price) obtained from the US Department of Energy website.

For example, during the month of June, if the lake level was declined by one foot then the hydroelectricity production would increase and it worth $42,000 while recreational benefits would decline by $531,000 due to an estimated decrease in the number of visitors by 3,000 and the value of a visitor day decreased to $49.18. Thus, for Lake Tenkiller during the summer months' maintaining near 'normal lake level' for recreational use outweighed the reduction in revenue generated from hydroelectricity production.

Discussion

The results were interesting since neither urban and rural water supply uses nor recreational uses were concerned as primary use when the dam was constructed. Results showed that the opportunity cost of recreational values forgone may exceed the value of electricity generated. This differed from the results obtained by Ward et al. (1996) for reservoirs in New Mexico. This was in part because the number of monthly summer visitors to Lake Tenkiller varies between 400 to over 500 thousand and in part because head above the turbines was lower for Lake Tenkiller than for the Rio Chama Basin of New Mexico. The optimal management plan was also influenced by the head of the reservoir; if the reservoir had higher elevation (head) then in that case the value of hydroelectric power generation increased relative to the lake recreational benefits.

In case of Lake Tenkiller, if the lake was managed to maximize the hydroelectric power generation benefit, then it would be beneficial to increase the lake level to maximize the head above the turbine and released water during the peak average electricity demand months of June through August. When recreational values were considered, the summer months' lake level should not be more than the normal lake level. This was because any lake level above the normal level of 632 feet would reduce the visits in the month of June, July and August.

The historical lake level was compared with the optimization model lake level with and without recreational values in the objective function was represented in Figure V -1. Thus, from the historical lake level it was concluded that while managing the lake USACE was neither considering the hydropower values nor considering the recreational values of Lake Tenkiller. They were just maintaining an average of five feet below or above the normal pool of around 632 ft throughout the year.

Warner et al (1973) in their study calculated the hydroelectric power generation benefit derived from the Lake Tenkiller just by maintaining a normal lake level of 632 feet and assumed a constant price of electricity in order to avoid the uncertainty and complexity of the hydropower rate system. While, the study done by the Center for Business and Economic Research (2003) estimated the value of delaying the summer drawdown through the end of September for Tennessee TVA lakes was nearly $ 20 million, but they did not consider the other factors such as flood control and power generation.

This study considered the hydropower production values and recreational benefits as well as the urban & rural water supply uses while managing Lake Tenkiller. The results obtained from this study clearly showed that when recreational benefits were included in the objective function then the lake level should be maintained at around 632 feet during the months of June, July and August and in the case when recreational benefits were not included in the objective function then the lake level should be raised maximum above the head and release water during the summer months.

It was also found that for Lake Tenkiller, water should be released based on the economic benefits derived from the particular uses in particular month rather than just trying to maintain the normal lake level of around 632 feet above sea level throughout the year which was not maximizing the net social benefits.

CHAPTER VI

SUMMARY AND CONCLUSIONS

This model was very important in the context of testing several different management policies. This type of model could be used to identify the economic impacts of different types of allocation pattern by controlling the releases (through the gate) and the outflows (from the turbine). Due to the ability of the model to allocate water among multiple uses over different months and to change the optimal usage pattern under different condition made it unique and a valuable tool for the governmental policy analysis.

In this study two different management scenarios were considered while managing Lake Tenkiller. They were: (a) lake reservoir was managed considering both the marketed and non-marketed values (when recreation values were included in the objective of the optimization model) and (b) reservoir was managed only considering the marketed values (when recreational benefits were not included in the objective function). Finally, it was found that Lake Tenkiller should be managed considering both the marketed and non-marketed values rather than managing the lake only for marketed values as it generated more revenue.

This optimization model showed that the total benefits can be explicitly increased by considering both market and non-market uses when allocating Lake Tenkiller water among different uses. It also showed that the greatest changes in the resource allocation were in the timing of releases for power generation and the resulting effect on recreational visitors. The model also tends to maximize the recreational benefits by maintaining the lake level around the normal lake level of 632 feet above the sea level during the summer months of June, July and August.

This study showed that for Lake Tenkiller during the summer months, the gain arising from recreational benefits was much higher than the hydroelectric power generation benefits. The results showed that during the summer months the visitors were sensitive to the lake level that were both above and below the optimum level. For this lake it appeared that additional recreational values were more valuable than the additional hydropower generated during the summer months of June, July and August. Therefore, the lake level for Lake Tenkiller should be maintained around the normal pool of 632 feet during the summer months in order to maximize the net social benefits.

Results also showed that Lake Tenkiller water could be efficiently allocated based on the optimization model developed in this study. By efficient allocation, it means that the marginal benefits should be equalized for all uses i.e. the total benefits must not be increased by transferring water from one uses to another. In this study the marginal benefits derived from urban and rural water use equates the marginal benefits obtained from hydropower generation. While due to negative marginal benefits for recreational uses, when the lake level was below the normal pool of 632 shown in Table V-9. Thus it was not possible to equate the recreational use marginal benefits with other uses.

The results showed that the benefits derived from different uses of Lake Tenkiller water could be increased by using an optimization model. This optimization model would serve as an important tool to guide Oklahoma Water Resource Board (OWRB) for making decision to manage Lake Tenkiller and assure safe and reliable water supply in the future to meet all the water needs of Oklahomans. This research study was very important in the context of comprehensive water management plan since it considered both the marketed and non-marketed value of reservoir (Tenkiller) water and showed the efficient allocation pattern.

The modeling approach used in this study was very useful for the policy makers to compare different management scenarios and compare the impact of each strategy on the total benefits. This would definitely help them in testing different water management policies and implement them while managing a reservoir.

CHAPTER VII

LIMITATIONS

Presently, there were some limitations in this study. First, it was assumed that whatever amount of electricity was produced would be sold in the spot market. Secondly, in this study in-stream recreational benefit were explicitly considered and in the month of May when recreational values were included in the objective function there was a huge release of water that might affect the trout fishing.

Thus in future, these assumptions will be taken care by considering the hydropower demand and while managing the lake trout fishing benefits derived from in-stream recreational use would also be considered.

In future more benefits derived from the reservoir water use were to be considered and implicitly the flood control and in-stream recreational values were included in the objective function. More specific lake visitation function would be estimated considering other variables such as water quality. In this study it was assumed that the quantity of water demanded by the urban and rural water system was solely depended on the population while in reality there were many other factors such as household income, temperature and precipitation that might affect the urban and rural water demand that would be considered in the future. The optimization model was solved based on the inflows coming from the Illinois River and the rainfall (assumed to be exogenously given). In reality precipitation was unpredictable and there was some probability associated with it. Thus, in future risk and uncertainty associated with the inflows i.e. the stochastic nature of the model would be considered.

REFERENCES

Aribisala, J. O. “Water Use Forecast for Hydropower Generation.” *Journal of Engineering and Applied Sciences 2(1) (2007) 222-225.*

Babel M.S, A. Das Gupta and D.K. Nayak. “A Model for Optimal Allocation of Water to Competing Demands.” *Water Resources Management 19 (2005) 693-712.*

Bachrach, Miguel and William J. Vaughan. “Household Water Demand Estimation.” Working Paper, Inter-American Development Bank, New York, March 1994.

Badger, D.D. and W.M. Harper, 1975. “Assessment of Pool Elevation Effects on Recreation and Concession Operations at Tenkiller Ferry Lake.” Prepared for U.S. Army Corps of Engineers Tulsa District, Department of Agricultural Economics, Oklahoma State niversity, AE 7503.

Bielsa, Jorge and Rosa Duarte. “An Economic Model For Water Allocation In North Eastern Spain.” *Water Resource Development 17 (September 2001) 397-410.*

Boland, John J. “Forecasting Urban Water Use: Theory and Principles.” *Urban Water Demand Management and Planning.* Duane D. Baumann, John J. Boland and W. Michael Haneman eds. McGraw-Hill Inc, 1998.

Boyer, Tracy, Art Stoecker, Larry Sanders. *Decision Support Model for Optimal Water Pricing Protocol for Oklahoma Water Planning: Lake Tenkiller Case Study* .Stillwater Ok: Oklahoma Water Resource Research Institute, FY 2007

Brooke, Anthony, David Kendrik and Alexander Meeraus. *Gams: A User’s Guide, Release 2.25.* Massachusetts: Boyd & Fraser Publishing Company, 1992.

Carriker, Roy R. “Issue in Water Allocation: Who Gets To Use How Much For What?” *Farm Foundation, Increasing Understanding of Public Policies and Problem (1984) 83-89.*

Center for Business and Economic Research, 2003. Economic Effects of Lake Management Policy in East Tennessee, Center for Business and Economic Research, University ofTennessee, May.

Chatterjee, Bishu, Richard E. Howitt and Richard J. Sexton. "The Optimal Joint Provision of Water for Irrigation and Hydropower." *Journal of Environmental Economics and Management 36 (November 1998) 295-313.*

Davis, W.Y., D.M. Rodrigo, E.M. Optiz, B. Dziegielewski, D.D. Baumann, and J.J. Boland, 1987. IWR-MAIN Water Use Forcasting System, Version 5.1: User's Manual and System Description, Prep. for U.S. Army Corps of Engineers, Planning and Management Consultants, Ltd., Carbondale III., Dec.

Debnath, Deepayan, Art Stoecker, Tracy Boyer, Larry Sanders. "Optimal Allocation of Reservoir Water: A Case Study of Lake Tenkiller" Southern Agricultural Economic Association, Atlanta Jan 31-Feb 3, 2009

Draper, Stephen E. "Modification of Permits Based on Consumptive Use." Personal Communication. Carl Vinson Institute of Government, The University of Georgia, April 2002.

Duloy, J. H. and R. D. Norton. "Prices and Incomes in Linear Programming Models." *American Journal of Agricultural Economics 57 (November 1975) 591-600.*

Energy Information Administration- Official Energy Statistics from the US Government. Internet site: http://www.eia.doe.gov/cneaf/electricity/epm/table5_6_a.html (Accessed December 18, 2008).

Environmental Protection Agency. "EPANET2", Internet site: http://www.epa.gov/nrmrl/wswrd/dw/epanet.html. (Retrieved June 12th, 2008)

Faruqui, Naser I., Asit K. Biswas, and Murad J. Bino. *Water Management in Islam* Tokyo: UNU Press 2001.

George, Biju, Hector M Malano, Brian Davidson, Anju Gaur. "A Water Allocation Modeling Framework for the Musi Catchment, India." *Proceedings of the International Conference of Modeling & Simulation* Changmai (2007), Thailand.

Hanson, Terrill R., Luther Upton Hatch, and Howard C. Clonts. "Reservoir Water Level Impacts on Recreation, Property, and Nonuser Values." *Journal of the American Water Resources Association 38-4 (August 2002) 1007-1018.*

Jordan, Edward and Badger, Daniel. "Management considerations in operating municipal lake recreation enterprises in Oklahoma." *Agricultural Experiment Station, Oklahoma State University. Technical Report. 1977.*

Kadigi, Reuben M. J., Ntengua S. Y. Mdoe, Gasper C. Ashimogo, Sylvie Morardet. "Water for irrigation or hydropower generation?- Complex questions regarding water allocation in Tanzania. Agricultural Water Management 95 (2008) 984-992.

Mckenzie, Russell W. “Examining Reservoir Managing Practices: The Optimal Provision Of Water Resources Under Alternative Management Scenario.” Ph.D. dissertation, Oklahoma State University, Stillwater August 2003.

Oklahoma’s Beneficial Use Monitoring Program- Lakes Sampling 2006-2007 Draft Report. Internet Site: http://www.owrb.ok.gov/quality/monitoring/bump/pdf_bump/Current/Lakes/tenkiller_ferry.pdf

Oklahoma Municipal League, 2008. “Oklahoma Municipal Utility Costs”, Report of Oklahoma Conference of Mayors, Oklahoma Municipal League, Inc and Municipal Electric Systems of Oklahoma, 2002, 2008.

Oklahoma Water Resources Board, 2008. Tenkiller Ferry Lake Oklahoma Water Resources Board. Internet Site: www.owrb.state.ok.us.

Oklahoma Department of Environmental Quality. “Public Water Supply Systems Search”, 2008, Records from monthly operation reports filed by water system managers.

Qubàa, R., M. El-fade1 and M. R. Darwish. “Water pricing for multi-sectoral allocation: a case study.” *Water Resource Development 18 (December 2002) 523–544.*

ReVelle, C. 1999. Optimizing Reservoir Resources: Including a New Model for Reservoir Reliability, John Wiley & Sons, Inc., New York.

Roberts, David, Tracy Boyer and Jason Lusk. “Environmental Preference under uncertainty.” *Ecological Economics 66 (July 2008) 584-93.*

Safe Drinking Water Information System (SDWIS), Retrieved on June 2009 Internet Website: http://sdwis.deq.state.ok.us/

Shrestha, Bijaya P, Lucian Duckstein and Eugene Z. Stakhiv, “Fuzzy Rule-Based Modeling of Reservoir Operation.” *Journal of Water Resource Planning and Management 122(July/August) 1996.263-269.*

Singer, Judith D. “Using SAS PROC MIXED to Fit Multilevel Models, Hierarchical Models, and Individual Growth Models.” *Journal of Educational and Behavioral Statistics-24 (4)winter 1998 323-355.*

USACE, 2001 Tenkiller Wholesale Water Treatment and Conveyance System Study: Phase III-Additional Preliminary Designs and Cost Estimates. Planning Assistance to States Program, Prepared for Tenkiller Utilities Authority through Oklahoma Water Resources Board, Tulsa District, U.S. Army Corps of Engineers. January 2001.

United States Census Bureau. “American Factfinder.”, 2008 from http://factfinder.census.gov.

USACE,1995-2007. TENO2: Tenkiller Lake, Real Time Lake Information, Internet Site:http://www.swt-wc.usace.army.mil/TENK.lakepage.html.

USACE, 1995-2000. WCDS Tulsa District:Tenkiller Lake, Hydropower Generation Information, Internet site: http://www.swt-wc.usace.army.mil/PowerGen.html.

Warner, L, D.D. Badger, and G.M. Lage, 1973. "Impact study of the Construction and Operation of the Tenkiller Ferry Lake, Oklahoma". Research Foundation, Oklahoma State University.

Ward, Frank A. and Thomas P. Lynch, "Integrated River Basin Optimization: Modeling Economic and Hydrologic Interdependence." *Water Resources Bulletin. 32, (December 1996): 1127-38.*

Winpenny, James, "Managing Water as an Economic Resource." Routledge,.Department of Agricultural Economics, Wye College, University of London.1994, 133 pp.

Wurbs, Ralph A. "Reservoir Water Management." *Water Resource Updates, Journal of Universities council on water resources 106 (Summer 1997).*

APPENDIXES

APPENDIX A-- Gams Code And The Results For The Optimization Model When Recreational Benefits Were Included In The Objective Function

```
option limrow=0, limcol=0
option nlp=minos
sets m month  /1*12/
J   Total Benefits Derived Urban & Rural water supply use and supply cost of
water in a particular month
/jan1,jan2,jan3,janProd,feb1,feb2,feb3,febprod,mar1,mar2,mar3,marprod,apr1,apr2,
apr3,aprprod,may1,may2,may3,mayprod,jun1,jun2,jun3,junprod,
jul1, jul2, jul3, julprod,aug1, aug2, aug3, augprod,
sep1,sep2,sep3,sepprod,oct1,oct2,oct3,octprod,nov1,nov2,nov3,novprod,dec1,dec2,d
ec3,decprod /
I  Amount of Month Water Demand by the Urban & Rural water use and the convexity
condition
/JanQd,JanConvex,febQd,febconvex,marQd,marconvex,aprqd,aprconvex,mayqd,mayconvex
,junqd,junconvex,
julqd,julconvex,augqd,augconvex,sepqd,sepconvex,octqd,octconvex,novqd,novconvex,
decqd,decconvex/
scalars
Intecept Estimated Intercept of the Visitation Equation /103733/
SlopeV Estimated Slope coefficient of the Visitation Equation with average
monthly lake level-632(normal lake level) /2642/
Aprl April Dummy Variable Coefficient of the Visitation Equation/187173/
May May Dummy Variable Coefficient of the Visitation Equation/285804/
jun June Dummy Variable Coefficient of the Visitation Equation/446102/
jul July Dummy Variable Coefficient of the Visitation Equation/505158/
aug August Dummy Variable Coefficient of the Visitation Equation/419897/
Sept September Dummy Variable Coefficient of the Visitation Equation/221399/
sqjuau Slope coefficient of the square of June & august (lake level -632)/254/
sqjul Slope coefficient of the square of July (lake level -632)  /1072/
Tsumr time trend only for the month of June July & August for 2010/10/
turbine Head of the Turbine /502/
value Slope Coefficient of the Hydroelectric Power Generation Equation/0.232457/
```

```
price1 Value of visitors per Day/50/
Slope Intercept of the equation relating the lake level and Lake
Volume/564.56301/
power Slope of the linear term of the equation relating the lake level and lake
volume/0.0001287/
sqpower Slope of the quadratic term of the equation relating the lake level and
lake volume/-0.000000000039105/
Parameter c(J) Total Benefits Derived Urban & Rural water supply use for
different water demands and supply cost of water in a particular month
/ jan1       11089634
  jan2       11090625.94
  jan3       11093392.27
  janprod   -257.64
  feb1       9522928.09
  feb2       9523922.091
  feb3       9525523.227
  febprod   -257.64
  mar1       10060169.93
  mar2       10060861.77
  mar3       10061487.35
  marprod   -257.64
  apr1       9587810.196
  apr2       9588814.156
  apr3       9591593.468
  aprprod   -257.64
  may1       2388208.012
  may2       2389187.597
  may3       2391580.958
  mayprod   -257.64
  jun1       2550596.786
  jun2       2551576.237
  jun3       2552121.568
  junprod   -257.64
  jul1       3176882.785
  jul2       3177861.808
  jul3       3178851.729
  julprod   -257.64
  aug1       3187438.022
  aug2       3188417.042
  aug3       3190768.298
  augprod   -257.65
  sep1       2767745.751
```

```
  sep2       2768725.037
  sep3       2770351.971
  sepprod   -257.64
  oct1       11826138.6
  oct2       11827129.29
  oct3       11834257.15
  octprod   -257.64
  nov1       10509442.23
  nov2       10510434.65
  nov3       10518971.47
  novprod    -257.64
  dec1       10504564.51
  dec2       10505556.95
  dec3       10505607.34
  decprod    -257.64/;
parameter B(I)    Monthly Water Demand constraints and Convexity Constraints
/ JanQd     0
  JanConvex 1
  febQd     0
  febconvex 1
  marQd     0
  marconvex 1
  aprQd     0
  aprconvex 1
  mayqd     0
  mayconvex 1
  junqd     0
  junconvex 1
  julqd     0
  julconvex 1
  augqd     0
  augconvex 1
  sepqd     0
  sepconvex 1
  octqd     0
  octconvex 1
  novqd     0
  novconvex 1
  decqd     0
  decconvex 1/;
```

Table A(i,j) Linearization of the quadratic form of the net social welfare obtained from the urban & rural water supply with ith quantity demand and jth benefits

	jan1	jan2	jan3	janProd	feb1	feb2	feb3	febprod	mar1	mar2	mar3	marprod
JanQd	839.69	840.69	905	-1								
JanConvex	1	1	1									
febQd					720.94	721.94	778	-1				
febconvex					1	1	1					
marQd									761.64	762.64	823	-1
marconvex									1	1	1	

+

	apr1	apr2	apr3	aprprod	may1	may2	may3	mayprod	jun1	jun2	jun3	junprod
aprQd	725.85	726.85	782	-1								
aprconvex	1	1	1									
mayqd					813.98	814.98	1220	-1				
mayconvex					1	1	1					
junqd									869.37	870.37	1305	-1
junconvex									1	1	1	

+

	jul1	jul2	jul3	julprod	aug1	aug2	aug3	augprod	sep1	sep2	sep3	sepprod
julqd	1083	1084	1625	-1								
julconvex	1	1	1									
augqd					1086.6	1087.6	1629	-1				
augconvex					1	1	1					
sepqd									943.44	944.44	1415	-1
sepconvex									1	1	1	

+	oct1	oct2	oct3	octprod	nov1	nov2	nov3	novprod	dec1	dec2	dec3	decprod
octqd	895.53	896.53	960	-1								
octconvex	1	1	1									
novqd					795.72	796.72	850	-1				
novconvex					1	1	1					
decqd									796.35	796.35	860	-1
decconvex									1	1	1	

variables

hydropower release(m) Release for Hydroelectric power generation,

bvol(m) Beginning Volume of Water in each month,

Inflow(m) Inflow of water to the lake Tenkiller in each month (exogenously given),

level(m) Lake Level in each month,

Head(m) Difference between the Lake Level and the height of the turbine,

HB(m) Hydroelectric power generation Benefits in each months,

hydropower1 Total amount of hydropower produced in a year (12 months)in MWH,

hydro(m) Hydropower produced in each months,

hydropower(m) Hydropower produced in each months in MWH,

visit(m) Lake visitation in each month,

visitors Total number of visitor over the year 2010,

RecreationBen Total Recreational Benefits,

HydropowerBen Total Hydroelectric power generation benefits,

totben Total Benefits,

RWS Urban & Rural Water Supply Benefits,

X(j) Urban & Rural Water Supply use demand in each months,

```
seepage(m) amount of seepage in each months (exogenously given),
release(m) amount of water released in each months for other uses;
positive variables
hydropowerrelease(m),bvol(m),Inflow(m),level(m),Head(m),hypower(m),visit(m),x(j)
,HB(m),release(m),seepage(m);
equations
obj Objective Function,
obj1 Recreational Benefits Equation,
obj2 Hydropower Benefits Equation,
obj3 Urban & Rural water supply Benefits Equation,
mod1 January Mass Balance Equation,
mod2 February Mass Balance Equation,
mod3 March Mass Balance Equation,
mod4 April Mass Balance Equation,
mod5 May Mass Balance Equation,
mod6 June Mass Balance Equation,
mod7 July Mass Balance Equation,
mod8 August Mass Balance Equation,
mod9 September Mass Balance Equation,
mod10 October Mass Balance Equation,
mod11 November Mass Balance Equation,
mod12 December Mass Balance Equation,
eqhead(m) Calculating Head of the Turbine in each Month,
eqpow(m) Amount of Hydropower produced in each month,
eqhydropower(m) Amount of Hydropower produced in each month in MWH,
lev1 Lake Level in the month of January,
lev2 Lake Level in the month of February,
lev3 Lake Level in the month of March,
lev4 Lake Level in the month of April,
lev5 Lake Level in the month of May,
lev6 Lake Level in the month of June,
lev7 Lake Level in the month of July,
lev8 Lake Level in the month of August,
lev9 Lake Level in the month of September,
lev10 Lake Level in the month of October,
lev11 Lake Level in the month of November,
lev12 Lake Level in the month of December,
visit1 Lake Visitation in the month of January,
visit2 Lake Visitation in the month of February,
visit3 Lake Visitation in the month of March,
visit4 Lake Visitation in the month of April,
visit5 Lake Visitation in the month of May,
```

```
visit6 Lake Visitation in the month of June,
visit7 Lake Visitation in the month of July,
visit8 Lake Visitation in the month of August,
visit9 Lake Visitation in the month of September,
visit10 Lake Visitation in the month of October,
visit11 Lake Visitation in the month of November,
visit12 Lake Visitation in the month of December,
HB1 Hydroelectric power generation benefits in January,
HB2 Hydroelectric power generation benefits in February,
HB3 Hydroelectric power generation benefits in March,
HB4 Hydroelectric power generation benefits in April,
HB5 Hydroelectric power generation benefits in May,
HB6 Hydroelectric power generation benefits in June,
HB7 Hydroelectric power generation benefits in July,
HB8 Hydroelectric power generation benefits in August,
HB9 Hydroelectric power generation benefits in September,
HB10 Hydroelectric power generation benefits in October,
HB11 Hydroelectric power generation benefits in November,
HB12 Hydroelectric power generation benefits in December,
eqvisitors Total number of visitors in the whole year 2010,
eqhypower1 total amount of electricity produced the year,
rows(i) constraints satisfying the convexity condition;
mod1..bvol('1')+inflow('1')-hydropowerrelease('1')-release('1')-x('janprod')-
seepage('1')=e=bvol('2');
mod2..bvol('2')+inflow('2')-hydropowerrelease('2')-release('2')-x('febprod')-
seepage('2')=e=bvol('3');
mod3..bvol('3')+inflow('3')-hydropowerrelease('3')-release('3')-x('marprod')-
seepage('3')=e=bvol('4');
mod4..bvol('4')+inflow('4')-hydropowerrelease('4')-release('4')-x('aprprod')-
seepage('4')=e=bvol('5');
mod5..bvol('5')+inflow('5')-hydropowerrelease('5')-release('5')-x('mayprod')-
seepage('5')=e=bvol('6');
mod6..bvol('6')+inflow('6')-hydropowerrelease('6')-release('6')-x('junprod')-
seepage('6')=e=bvol('7');
mod7..bvol('7')+inflow('7')-hydropowerrelease('7')-release('7')-x('julprod')-
seepage('7')=e=bvol('8');
mod8..bvol('8')+inflow('8')-hydropowerrelease('8')-release('8')-x('augprod')-
seepage('8')=e=bvol('9');
mod9..bvol('9')+inflow('9')-hydropowerrelease('9')-release('9')-x('sepprod')-
seepage('9')=e=bvol('10');
mod10..bvol('10')+inflow('10')-hydropowerrelease('10')-release('10')-
x('octprod')-seepage('10')=e=bvol('11');
```

```
mod11..bvol('11')+inflow('11')-hydropowerrelease('11')-release('11')-
x('novprod')-seepage('11')=e=bvol('12');
mod12..bvol('12')+inflow('12')-hydropowerrelease('12')-release('12')-
x('decprod')-seepage('12')=e=bvol('1');
lev1..Level('1')=E=Slope+power*(bvol('2'))+sqpower*(bvol('2'))**2;
lev2..Level('2')=E=Slope+power*(bvol('3'))+sqpower*(bvol('3'))**2;
lev3..Level('3')=E=Slope+power*(bvol('4'))+sqpower*(bvol('4'))**2;
lev4..Level('4')=E=Slope+power*(bvol('5'))+sqpower*(bvol('5'))**2;
lev5..Level('5')=E=Slope+power*(bvol('6'))+sqpower*(bvol('6'))**2;
lev6..Level('6')=E=Slope+power*(bvol('7'))+sqpower*(bvol('7'))**2;
lev7..Level('7')=E=Slope+power*(bvol('8'))+sqpower*(bvol('8'))**2;
lev8..Level('8')=E=Slope+power*(bvol('9'))+sqpower*(bvol('9'))**2;
lev9..Level('9')=E=Slope+power*(bvol('10'))+sqpower*(bvol('10'))**2;
lev10..Level('10')=E=Slope+power*(bvol('11'))+sqpower*(bvol('11'))**2;
lev11..Level('11')=E=Slope+power*(bvol('12'))+sqpower*(bvol('12'))**2;
lev12..Level('12')=E=Slope+power*(bvol('12')+inflow('12')-
hydropowerrelease('12')-x('decprod')-release('12')-seepage('12'))+
sqpower*(bvol('12')+inflow('12')-hydropowerrelease('12')-x('decprod')-
release('12')-seepage('12'))**2;
visit1..visit('1')=e=min((Intecept+ SlopeV*(level('1')-632)),Intecept);
visit2..visit('2')=e=min((Intecept+ SlopeV*(level('2')-632)),Intecept);
visit3..visit('3')=e=min((Intecept+ SlopeV*(level('3')-632)),Intecept);
visit4..visit('4')=e=min((Aprl+ SlopeV*(level('4')-632)),Aprl);
visit5..visit('5')=e=min((May+ SlopeV*(level('5')-632)),May);
visit6..visit('6')=e=(jun+SlopeV*min((level('6')-632),0)+2654*Tsumr-
sqjuau*(level('6')-632)*(level('6')-632));
visit7..visit('7')=e=(jul+SlopeV*min((level('7')-632),0)+2654*Tsumr-
sqjul*(level('7')-632)*(level('7')-632));
visit8..visit('8')=e=(aug+SlopeV*min((level('8')-632),0)+2654*Tsumr-
sqjuau*(level('8')-632)*(level('8')-632));
visit9..visit('9')=e=min((Sept+ SlopeV*(level('9')-632)),Sept);
visit10..visit('10')=e=min((Intecept+ SlopeV*(level('10')-632)),Intecept);
visit11..visit('11')=e=min((Intecept+ SlopeV*(level('11')-632)),Intecept);
visit12..visit('12')=e=min((Intecept+ SlopeV*(level('12')-632)),Intecept);
eqhead(m)..Head(m)=E=Level(m)-turbine;
eqpow(m)..hydro(m)=E=value*Head(m)*hydropowerrelease(m)/3960;
eqhydropower(m)..hydropower(m)=E=hydro(m)*10.55;
eqvisitors..visitors=E=(sum(m,visit(m)));
eqhypower1..hydropower1=E=(sum(m,hydropower(m)));
obj2.. HydropowerBen=E=(SUM(m,HB(m)));
HB1..HB('1')=E=89*hydropower('1');
HB2..HB('2')=E=89*hydropower('2');
```

```
HB3..HB('3')=E=89*hydropower('3');
HB4..HB('4')=E=89*hydropower('4');
HB5..HB('5')=E=90.5*hydropower('5');
HB6..HB('6')=E=94.7*hydropower('6');
HB7..HB('7')=E=96.6*hydropower('7');
HB8..HB('8')=E=96.5*hydropower('8');
HB9..HB('9')=E=94.1*hydropower('9');
HB10..HB('10')=E=91.18*hydropower('10');
HB11..HB('11')=E=88*hydropower('11');
HB12..HB('12')=E=88*hydropower('12');
obj1..RecreationBen=E=price1*(sum(m,visit(m)));
obj3..RWS=e= sum(j,c(j)*x(j));
rows(i)..Sum(j,A(I,J)*X(j))=L=B(i);
obj..totben=e=HydropowerBen+RWS+RecreationBen;
bvol.fx('1')=644642;
Inflow.fx('1')=139529;Inflow.fx('2')=115190;Inflow.fx('3')=134488;Inflow.fx('4')
=152338;Inflow.fx('5')=141149; Inflow.fx('6')=132882;
Inflow.fx('7')=65106;Inflow.fx('8')=27618;Inflow.fx('9')=35776;Inflow.fx('10')=3
4665;Inflow.fx('11')=95504;Inflow.fx('12')=93730;
seepage.fx('1')=5517;seepage.fx('2')=14776;seepage.fx('3')=6055;seepage.fx('4')=
14218;seepage.fx('5')=15956;seepage.fx('6')=15446;
seepage.fx('7')=11902;seepage.fx('8')=7433;seepage.fx('9')=9477;seepage.fx('10')
=1557;seepage.fx('11')=9497;seepage.fx('12')=5149;
level.up(m)=645;level.lo(m)=630;
level.up('1')=635;
hydropower.up(m)=24500;
model totalbenefit/all/;
totalbenefit.scaleopt=1;
solve totalbenefit using nlp maximizing totben;
```

```
               S O L V E      S U M M A R Y

MODEL   totalbenefit        OBJECTIVE  totben
     TYPE    NLP                 DIRECTION  MAXIMIZE
     SOLVER  MINOS               FROM LINE  285

**** SOLVER STATUS     1 NORMAL COMPLETION
**** MODEL STATUS      2 LOCALLY OPTIMAL
**** OBJECTIVE VALUE        230722322.7198

 RESOURCE USAGE, LIMIT          0.098      1000.000
 ITERATION COUNT, LIMIT       268         10000
 EVALUATION ERRORS              0             0

Work space allocated           --    1.31 Mb

EXIT - Optimal Solution found, objective:       0.2307223E+09
```

```
 Major, Minor Iterations    11     268
 Funobj, Funcon calls     1173    1173
 Superbasics                 6
 Aggregations                5
 Interpreter Usage        0.05    48.0%

                       LOWER     LEVEL     UPPER    MARGINAL

---- EQU obj             .         .         .        1.000
---- EQU obj1            .         .         .        1.000
---- EQU obj2            .         .         .        1.000
---- EQU mod1            .         .         .       -7.331
---- EQU mod2            .         .         .       -7.882
---- EQU mod3            .         .         .       -7.882
---- EQU mod4            .         .         .       -7.882
---- EQU mod5            .         .         .       -8.015
---- EQU mod6            .         .         .       -7.667
---- EQU mod7            .         .         .       -7.779
---- EQU mod8            .         .         .       -7.769
---- EQU mod9            .         .         .       -7.576
---- EQU mod10           .         .         .       -7.366
---- EQU mod11           .         .         .       -7.251
---- EQU mod12           .         .         .        3.881

  obj  Objective Function
  obj1  Recreational Benefits Equation
  obj2  Hydropower Benefits Equation
  obj3  Urban & Rural water supply Benefits Equation
  mod1  January Mass Balance Equation
  mod2  February Mass Balance Equation
  mod3  March Mass Balance Equation
  mod4  April Mass Balance Equation
  mod5  May Mass Balance Equation
  mod6  June Mass Balance Equation
  mod7  July Mass Balance Equation
  mod8  August Mass Balance Equation
  mod9  September Mass Balance Equation
  mod10  October Mass Balance Equation
  mod11  November Mass Balance Equation
  mod12  December Mass Balance Equation

---- EQU eqhead Calculating Head of the Turbine in each Month

      LOWER     LEVEL     UPPER    MARGINAL

1   -502.000  -502.000  -502.000  4653.963
2   -502.000  -502.000  -502.000   998.588
3   -502.000  -502.000  -502.000  3557.364
4   -502.000  -502.000  -502.000  7572.774
5   -502.000  -502.000  -502.000  6970.952
6   -502.000  -502.000  -502.000 17121.200
7   -502.000  -502.000  -502.000  3659.569
8   -502.000  -502.000  -502.000  1165.776
9   -502.000  -502.000  -502.000  1478.394
10  -502.000  -502.000  -502.000  1785.429
11  -502.000  -502.000  -502.000  2621.734
12  -502.000  -502.000  -502.000  7343.569
```

```
---- EQU eqpow Amount of Hydropower produced in each month

      LOWER     LEVEL     UPPER    MARGINAL

1       .         .         .      938.950
2       .         .         .      975.275
3       .         .         .      938.950
4       .         .         .      938.950
5       .         .         .      954.775
6       .         .         .      999.085
7       .         .         .     1019.130
8       .         .         .     1018.039
9       .         .         .      992.755
10      .         .         .      961.949
11      .         .         .      928.393
12      .         .         .      928.400

---- EQU eqhydropower Amount of Hydropower produced in each month in MWH

      LOWER     LEVEL     UPPER    MARGINAL

1       .         .         .       89.000
2       .         .         .       92.443
3       .         .         .       89.000
4       .         .         .       89.000
5       .         .         .       90.500
6       .         .         .       94.700
7       .         .         .       96.600
8       .         .         .       96.497
9       .         .         .       94.100
10      .         .         .       91.180
11      .         .         .       87.999
12      .         .         .       88.000

                       LOWER     LEVEL     UPPER    MARGINAL

---- EQU lev1         564.563   564.563   564.563 -8313.537
---- EQU lev2         564.563   564.563   564.563   998.588
---- EQU lev3         564.563   564.563   564.563      EPS
---- EQU lev4         564.563   564.563   564.563 -2105.188
---- EQU lev5         564.563   564.563   564.563  5508.140
---- EQU lev6         564.563   564.563   564.563 -1457.932
---- EQU lev7         564.563   564.563   564.563   131.381
---- EQU lev8         564.563   564.563   564.563  1137.653
---- EQU lev9         564.563   564.563   564.563  1478.394
---- EQU lev10        564.563   564.563   564.563  1785.429
---- EQU lev11        564.563   564.563   564.563  2621.734
---- EQU lev12        564.563   564.563   564.563 1.3944E+5
---- EQU visit1          .         .         .       50.000
---- EQU visit2          .         .         .       50.000
---- EQU visit3          .         .         .       50.000
---- EQU visit4          .         .         .       50.000
---- EQU visit5          .         .         .       50.000
---- EQU visit6     4.7264E+5 4.7264E+5 4.7264E+5    50.000
---- EQU visit7     5.3170E+5 5.3170E+5 5.3170E+5    50.000
---- EQU visit8     4.4644E+5 4.4644E+5 4.4644E+5    50.000
```

```
---- EQU visit9          .         .         .       50.000
---- EQU visit10         .         .         .       50.000
---- EQU visit11         .         .         .       50.000
---- EQU visit12         .         .         .       50.000
---- EQU HB1             .         .         .        1.000
---- EQU HB2             .         .         .        1.000
---- EQU HB3             .         .         .        1.000
---- EQU HB4             .         .         .        1.000
---- EQU HB5             .         .         .        1.000
---- EQU HB6             .         .         .        1.000
---- EQU HB7             .         .         .        1.000
---- EQU HB8             .         .         .        1.000
---- EQU HB9             .         .         .        1.000
---- EQU HB10            .         .         .        1.000
---- EQU HB11            .         .         .        1.000
---- EQU HB12            .         .         .        1.000
---- EQU eqvisitors      .         .         .         EPS
---- EQU eqhypower1      .         .         .         EPS

  lev1  Lake Level in the month of January
  lev2  Lake Level in the month of Febuary
  lev3  Lake Level in the month of March
  lev4  Lake Level in the month of April
  lev5  Lake Level in the month of May
  lev6  Lake Level in the month of June
  lev7  Lake Level in the month of July
  lev8  Lake Level in the month of August
  lev9  Lake Level in the month of September
  lev10  Lake Level in the month of October
  lev11  Lake Level in the month of November
  lev12  Lake Level in the month of December
  visit1  Lake Visitation in the month of January
  visit2  Lake Visitation in the month of February
  visit3  Lake Visitation in the month of March
  visit4  Lake Visitation in the month of April
  visit5  Lake Visitation in the month of May
  visit6  Lake Visitation in the month of June
  visit7  Lake Visitation in the month of July
  visit8  Lake Visitation in the month of August
  visit9  Lake Visitation in the month of September
  visit10  Lake Visitation in the month of October
  visit11  Lake Visitation in the month of November
  visit12  Lake Visitation in the month of December
  HB1  Hydroelectric power generation benefits in January
  HB2  Hydroelectric power generation benefits in February
  HB3  Hydroelectric power generation benefits in March
  HB4  Hydroelectric power generation benefits in April
  HB5  Hydroelectric power generation benefits in May
  HB6  Hydroelectric power generation benefits in June
  HB7  Hydroelectric power generation benefits in July
  HB8  Hydroelectric power generation benefits in August
  HB9  Hydroelectric power generation benefits in September
  HB10  Hydroelectric power generation benefits in October
  HB11  Hydroelectric power generation benefits in November
  HB12  Hydroelectric power generation benefits in December
  eqvisitors  Total number of visitors in the whole year 2010
  eqhypower1  total amount of electricity produced the year
```

```
---- EQU rows  constraints satisfying the convexity condition

             LOWER     LEVEL     UPPER    MARGINAL

JanQd         -INF       .         .       264.971
JanConvex     -INF      1.000     1.000 1.0868E+7
febQd         -INF       .         .       265.590
febconvex     -INF      1.000     1.000 9.3322E+6
marQd         -INF       .         .       265.522
marconvex     -INF      1.000     1.000 9.8584E+6
aprqd         -INF       .         .       265.522
aprconvex     -INF      1.000     1.000 9.3958E+6
mayqd         -INF       .         .       265.655
mayconvex     -INF      1.000     1.000 2.1727E+6
junqd         -INF       .         .       265.307
junconvex     -INF      1.000     1.000 2.3207E+6
julqd         -INF       .         .       265.419
julconvex     -INF      1.000     1.000 2.8901E+6
augqd         -INF       .         .       265.419
augconvex     -INF      1.000     1.000 2.8997E+6
sepqd         -INF       .         .       265.216
sepconvex     -INF      1.000     1.000 2.5182E+6
octqd         -INF       .         .       264.983
octconvex     -INF      1.000     1.000 1.1590E+7
novqd         -INF       .         .       264.881
novconvex     -INF      1.000     1.000 1.0299E+7
decqd         -INF       .         .       264.685
decconvex     -INF      1.000     1.000 1.0295E+7

---- VAR hydropower  Release for Hydroelectric power generation

      LOWER     LEVEL     UPPER    MARGINAL

1       .    84437.035     +INF       .
2       .    17442.637     +INF       .
3       .    64541.405     +INF       .
4       .    1.3739E+5     +INF       .
5       .    1.2438E+5     +INF       .
6       .    2.9193E+5     +INF       .
7       .    61172.028     +INF  4.3856E-5
8       .    19507.573     +INF       .
9       .    25368.836     +INF       .
10      .    31618.629     +INF       .
11      .    48107.113     +INF       .
12      .    1.3475E+5     +INF       .

---- VAR bvol  Beginning Volume of Water in each month

      LOWER     LEVEL     UPPER    MARGINAL

1  6.4464E+5 6.4464E+5 6.4464E+5    11.201
2       .    6.9338E+5     +INF       .
3       .    7.7563E+5     +INF       .
4       .    8.3875E+5     +INF       .
5       .    8.3875E+5     +INF       .
6       .    8.3875E+5     +INF       .
```

```
7        .    6.6339E+5     +INF        .
8        .    6.5433E+5     +INF        .
9        .    6.5392E+5     +INF     -0.105
10       .    6.5391E+5     +INF     -0.118
11       .    6.5450E+5     +INF      0.036
12       .    6.9161E+5     +INF        .

---- VAR Inflow Inflow of water to the lake Tenkiller in each month
(exogenously given)

      LOWER     LEVEL     UPPER    MARGINAL

1  1.3953E+5 1.3953E+5 1.3953E+5     7.331
2  1.1519E+5 1.1519E+5 1.1519E+5     7.950
3  1.3449E+5 1.3449E+5 1.3449E+5     7.882
4  1.5234E+5 1.5234E+5 1.5234E+5     7.882
5  1.4115E+5 1.4115E+5 1.4115E+5     8.015
6  1.3288E+5 1.3288E+5 1.3288E+5     7.667
7  65106.000 65106.000 65106.000     7.779
8  27618.000 27618.000 27618.000     7.769
9  35776.000 35776.000 35776.000     7.576
10 34665.000 34665.000 34665.000     7.343
11 95504.000 95504.000 95504.000     7.241
12 93730.000 93730.000 93730.000     7.045

---- VAR level Lake Level in each month

      LOWER     LEVEL     UPPER    MARGINAL

1    635.000   635.000   635.000 12967.500
2    630.000   640.861   645.000        .
3    630.000   645.000   645.000  3557.364
4    630.000   645.000   645.000  9677.962
5    630.000   645.000   645.000  1462.812
6    630.000   632.731   645.000        .
7    630.000   632.033   645.000        .
8    630.000   632.001   645.000        .
9    630.000   632.000   645.000        .
10   630.000   632.046   645.000        .
11   630.000   634.868   645.000        .
12   630.000   631.278   645.000        .

---- VAR Head difference between the Lake Level and the height of the
turbine

      LOWER     LEVEL     UPPER    MARGINAL

1        .      133.000     +INF        .
2        .      138.861     +INF        .
3        .      143.000     +INF        .
4        .      143.000     +INF        .
5        .      143.000     +INF        .
6        .      130.731     +INF        .
7        .      130.033     +INF        .
8        .      130.001     +INF        .
9        .      130.000     +INF        .
10       .      130.046     +INF        .
```

```
11      .      132.868     +INF       .
12      .      129.278     +INF       .

---- VAR HB Hydroelectric power generation Benefits in each months

      LOWER     LEVEL     UPPER    MARGINAL

1       .    6.1898E+5     +INF       .
2       .    1.3350E+5     +INF       .
3       .    5.0870E+5     +INF       .
4       .    1.0829E+6     +INF       .
5       .    9.9685E+5     +INF       .
6       .    2.2383E+6     +INF       .
7       .    4.7586E+5     +INF       .
8       .    1.5156E+5     +INF       .
9       .    1.9219E+5     +INF       .
10      .    2.3219E+5     +INF       .
11      .    3.4835E+5     +INF       .
12      .    9.4936E+5     +INF       .

                       LOWER     LEVEL     UPPER    MARGINAL

---- VAR hydropowe~     -INF   86820.653     +INF       .

  hydropower1 Total amount of hydropower produced in a year (12
months)in MWH

---- VAR hydro Hydropower produced in each months

      LOWER     LEVEL     UPPER    MARGINAL

1      -INF    659.223     +INF       .
2      -INF    142.180     +INF       .
3      -INF    541.779     +INF       .
4      -INF   1153.317     +INF       .
5      -INF   1044.064     +INF       .
6      -INF   2240.329     +INF       .
7      -INF    466.932     +INF       .
8      -INF    148.867     +INF       .
9      -INF    193.594     +INF       .
10     -INF    241.372     +INF       .
11     -INF    375.212     +INF       .
12     -INF   1022.577     +INF       .

---- VAR Hydropower produced in each month in MWH

      LOWER     LEVEL     UPPER    MARGINAL

1   1500.000  6954.798 24500.000      .
2   1500.000  1500.000 24500.000    -3.443
3   1500.000  5715.765 24500.000      .
4   1500.000 12167.491 24500.000      .
5   1500.000 11014.875 24500.000      .
6   1500.000 23635.475 24500.000      .
7   1500.000  4926.132 24500.000      .
8   1500.000  1570.544 24500.000     0.003
9   1500.000  2042.414 24500.000      .
```

```
10  1500.000  2546.477 24500.000      .
11  1500.000  3958.492 24500.000 6.5924E-4
12  1500.000 10788.190 24500.000      .

---- VAR visit Lake Visitation in each month

      LOWER     LEVEL     UPPER    MARGINAL

1       .    1.0373E+5     +INF       .
2       .    1.0373E+5     +INF       .
3       .    1.0373E+5     +INF       .
4       .    1.8717E+5     +INF       .
5       .    2.8580E+5     +INF       .
6       .    4.7251E+5     +INF       .
7       .    5.3170E+5     +INF       .
8       .    4.4644E+5     +INF       .
9       .    2.2140E+5     +INF       .
10      .    1.0373E+5     +INF       .
11      .    1.0373E+5     +INF       .
12      .    1.0183E+5     +INF       .

                       LOWER     LEVEL     UPPER    MARGINAL

---- VAR visitors       -INF  2.7655E+6     +INF       .
---- VAR Recreatio~     -INF  1.3828E+8     +INF       .
---- VAR Hydropowe~     -INF  7.9287E+6     +INF       .
---- VAR totben         -INF  2.3072E+8     +INF       .
---- VAR RWS            -INF  8.4518E+7     +INF       .

  visitors  Total number of visitor over the year 2010
  RecreationBen  Total Recreational Benefits
  HydropowerBen  Total Hydroelectric power generation benefits
  totben  Total Benefits
  RWS  Urban & Rural Water Supply Benefits

---- VAR X Urban & Rural Water Supply use demand in each months

           LOWER     LEVEL     UPPER    MARGINAL

jan1         .         .        +INF   -726.969
jan2         .        1.000     +INF       .
jan3         .         .        +INF  -1.427E+4
janProd      .      840.690     +INF       .
feb1         .         .        +INF   -728.411
feb2         .        1.000     +INF       .
feb3         .         .        +INF  -1.329E+4
febprod      .      721.940     +INF       .
mar1         .         .        +INF   -426.318
mar2         .        1.000     +INF       .
mar3         .         .        +INF  -1.540E+4
marprod      .      762.640     +INF       .
apr1         .         .        +INF   -738.438
apr2         .        1.000     +INF       .
apr3         .         .        +INF  -1.186E+4
aprprod      .      726.850     +INF       .
may1         .         .        +INF   -713.930
may2         .        1.000     +INF       .
```

```
may3         .          .        +INF  -1.052E+5
mayprod      .      814.980     +INF       .
jun1         .          .        +INF   -714.144
jun2         .        1.000     +INF       .
jun3         .          .        +INF  -1.148E+5
junprod      .      870.370     +INF       .
jul1         .          .        +INF   -713.604
jul2         .        1.000     +INF       .
jul3         .          .        +INF  -1.426E+5
julprod      .     1084.000     +INF       .
aug1         .          .        +INF   -713.601
aug2         .        1.000     +INF       .
aug3         .          .        +INF  -1.413E+5
augprod      .     1087.600     +INF       .
sep1         .          .        +INF   -714.070
sep2         .        1.000     +INF       .
sep3         .          .        +INF  -1.232E+5
sepprod      .      944.440     +INF       .
oct1         .          .        +INF   -725.707
oct2         .        1.000     +INF       .
oct3         .          .        +INF  -9690.636
octprod      .      896.530     +INF       .
nov1         .          .        +INF   -727.539
nov2         .        1.000     +INF       .
nov3         .          .        +INF  -5576.041
novprod      .      796.720     +INF       .
dec1         .          .        +INF   -727.755
dec2         .        1.000     +INF       .
dec3         .          .        +INF  -1.680E+4
decprod      .      796.350     +INF       .

---- VAR seepage amount of seepage in each months (exogenously given)

      LOWER     LEVEL     UPPER    MARGINAL

1   5517.000  5517.000  5517.000    -7.331
2  14776.000 14776.000 14776.000    -7.950
3   6055.000  6055.000  6055.000    -7.882
4  14218.000 14218.000 14218.000    -7.882
5  15956.000 15956.000 15956.000    -8.015
6  15446.000 15446.000 15446.000    -7.667
7  11902.000 11902.000 11902.000    -7.779
8   7433.000  7433.000  7433.000    -7.769
9   9477.000  9477.000  9477.000    -7.576
10  1557.000  1557.000  1557.000    -7.343
11  9497.000  9497.000  9497.000    -7.241
12  5149.000  5149.000  5149.000    -7.045

---- VAR release amount of water released in each months for other uses

      LOWER     LEVEL     UPPER    MARGINAL

1       .         .        +INF     -7.331
2       .         .        +INF     -7.950
3       .         .        +INF     -7.882
4       .         .        +INF     -7.882
5       .         .        +INF     -8.015
```

```
6        .         .        +INF     -7.667
7        .         .        +INF     -7.779
8        .         .        +INF     -7.769
9        .         .        +INF     -7.576
10       .         .        +INF     -7.343
11       .         .        +INF     -7.241
12       .         .        +INF     -7.045
```

APPENDIX B-- Changes In GAMS Code And The Results For The Optimization Model When Recreational Benefits Were Not Included In The Objective Function

```
In this model only the Objective Function changes

obj..totben=e=HydropowerBen+RWS;


MODEL   totalbenefit        OBJECTIVE  totben
     TYPE    NLP                 DIRECTION  MAXIMIZE
     SOLVER  MINOS               FROM LINE  285

**** SOLVER STATUS     1 NORMAL COMPLETION
**** MODEL STATUS      2 LOCALLY OPTIMAL
**** OBJECTIVE VALUE         92626848.0057


 EXIT - Optimal Solution found, objective:       0.9262685E+08

 Major, Minor Iterations    28     299
 Funobj, Funcon calls      802     802
 Superbasics                 5
 Aggregations                5
 Interpreter Usage        0.04    21.4%


                       LOWER     LEVEL     UPPER    MARGINAL

---- EQU obj             .         .         .        1.000
---- EQU obj1            .         .         .         EPS
---- EQU obj2            .         .         .        1.000
---- EQU obj3            .         .         .        1.000
---- EQU mod1            .         .         .       -7.331
---- EQU mod2            .         .         .       -7.950
---- EQU mod3            .         .         .       -7.882
---- EQU mod4            .         .         .       -7.882
---- EQU mod5            .         .         .       -8.015
---- EQU mod6            .         .         .       -8.387
---- EQU mod7            .         .         .       -8.463
---- EQU mod8            .         .         .       -8.167
---- EQU mod9            .         .         .       -7.788
---- EQU mod10           .         .         .       -7.500
---- EQU mod11           .         .         .       -7.318
---- EQU mod12           .         .         .       -6.401

  obj  Objective Function
  obj1  Recreational Benefits Equation
  obj2  Hydropower Benefits Equation
  obj3  Urban & Rural water supply Benefits Equation
  mod1  January Mass Balance Equation
  mod2  February Mass Balance Equation
  mod3  March Mass Balance Equation
  mod4  April Mass Balance Equation
  mod5  May Mass Balance Equation
```

```
  mod6  June Mass Balance Equation
  mod7  July Mass Balance Equation
  mod8  August Mass Balance Equation
  mod9  September Mass Balance Equation
  mod10  October Mass Balance Equation
  mod11  November Mass Balance Equation
  mod12  December Mass Balance Equation

---- EQU eqhead Calculating Head of the Turbine in each Month

      LOWER     LEVEL     UPPER    MARGINAL

1   -502.000  -502.000  -502.000  4653.963
2   -502.000  -502.000  -502.000   998.588
3   -502.000  -502.000  -502.000  3557.364
4   -502.000  -502.000  -502.000  7572.774
5   -502.000  -502.000  -502.000  6970.952
6   -502.000  -502.000  -502.000  6836.289
7   -502.000  -502.000  -502.000  4553.808
8   -502.000  -502.000  -502.000  5346.713
9   -502.000  -502.000  -502.000  3949.048
10  -502.000  -502.000  -502.000  2439.326
11  -502.000  -502.000  -502.000  3639.196
12  -502.000  -502.000  -502.000  8314.537

---- EQU eqpow  Amount of Hydropower produced in each month

      LOWER     LEVEL     UPPER    MARGINAL

1       .         .         .      938.950
2       .         .         .      975.275
3       .         .         .      938.950
4       .         .         .      938.950
5       .         .         .      954.775
6       .         .         .      999.085
7       .         .         .     1019.130
8       .         .         .     1018.075
9       .         .         .      992.755
10      .         .         .      961.949
11      .         .         .      928.400
12      .         .         .      928.400

---- EQU eqhydropower  Amount of Hydropower produced in each month in
MWH

      LOWER     LEVEL     UPPER    MARGINAL

1       .         .         .       89.000
2       .         .         .       92.443
3       .         .         .       89.000
4       .         .         .       89.000
5       .         .         .       90.500
6       .         .         .       94.700
7       .         .         .       96.600
8       .         .         .       96.500
9       .         .         .       94.100
10      .         .         .       91.180
```

```
11       .         .         .       88.000
12       .         .         .       88.000

                       LOWER     LEVEL     UPPER    MARGINAL

---- EQU lev1         564.563   564.563   564.563 -8313.537
---- EQU lev2         564.563   564.563   564.563   998.588
---- EQU lev3         564.563   564.563   564.563      EPS
---- EQU lev4         564.563   564.563   564.563 -2105.188
---- EQU lev5         564.563   564.563   564.563 -5894.527
---- EQU lev6         564.563   564.563   564.563 -1209.448
---- EQU lev7         564.563   564.563   564.563  4553.808
---- EQU lev8         564.563   564.563   564.563  5346.713
---- EQU lev9         564.563   564.563   564.563  3949.048
---- EQU lev10        564.563   564.563   564.563  2439.326
---- EQU lev11        564.563   564.563   564.563  3639.196
---- EQU lev12        564.563   564.563   564.563  8314.537
---- EQU visit1           .         .         .        EPS
---- EQU visit2           .         .         .        EPS
---- EQU visit3           .         .         .        EPS
---- EQU visit4           .         .         .        EPS
---- EQU visit5           .         .         .        EPS
---- EQU visit6     4.7264E+5 4.7264E+5 4.7264E+5      EPS
---- EQU visit7     5.3170E+5 5.3170E+5 5.3170E+5      EPS
---- EQU visit8     4.4644E+5 4.4644E+5 4.4644E+5      EPS
---- EQU visit9           .         .         .        EPS
---- EQU visit10          .         .         .        EPS
---- EQU visit11          .         .         .        EPS
---- EQU visit12          .         .         .        EPS
---- EQU HB1              .         .         .       1.000
---- EQU HB2              .         .         .       1.000
---- EQU HB3              .         .         .       1.000
---- EQU HB4              .         .         .       1.000
---- EQU HB5              .         .         .       1.000
---- EQU HB6              .         .         .       1.000
---- EQU HB7              .         .         .       1.000
---- EQU HB8              .         .         .       1.000
---- EQU HB9              .         .         .       1.000
---- EQU HB10             .         .         .       1.000
---- EQU HB11             .         .         .       1.000
---- EQU HB12             .         .         .       1.000
---- EQU eqvisitors       .         .         .        EPS
---- EQU eqhypower1       .         .         .        EPS

  lev1  Lake Level in the month of January
  lev2  Lake Level in the month of Febuary
  lev3  Lake Level in the month of March
  lev4  Lake Level in the month of April
  lev5  Lake Level in the month of May
  lev6  Lake Level in the month of June
  lev7  Lake Level in the month of July
  lev8  Lake Level in the month of August
  lev9  Lake Level in the month of September
  lev10  Lake Level in the month of October
  lev11  Lake Level in the month of November
  lev12  Lake Level in the month of December
  visit1  Lake Visitation in the month of January
```

```
  visit2  Lake Visitation in the month of February
  visit3  Lake Visitation in the month of March
  visit4  Lake Visitation in the month of April
  visit5  Lake Visitation in the month of May
  visit6  Lake Visitation in the month of June
  visit7  Lake Visitation in the month of July
  visit8  Lake Visitation in the month of August
  visit9  Lake Visitation in the month of September
  visit10  Lake Visitation in the month of October
  visit11  Lake Visitation in the month of November
  visit12  Lake Visitation in the month of December
  HB1  Hydroelectric power generation benefits in January
  HB2  Hydroelectric power generation benefits in February
  HB3  Hydroelectric power generation benefits in March
  HB4  Hydroelectric power generation benefits in April
  HB5  Hydroelectric power generation benefits in May
  HB6  Hydroelectric power generation benefits in June
  HB7  Hydroelectric power generation benefits in July
  HB8  Hydroelectric power generation benefits in August
  HB9  Hydroelectric power generation benefits in September
  HB10  Hydroelectric power generation benefits in October
  HB11  Hydroelectric power generation benefits in November
  HB12  Hydroelectric power generation benefits in December
  eqvisitors  Total number of visitors in the whole year 2010
  eqhypower1  total amount of electricity produced the year

---- EQU rows  constraints satisfying the convexity condition

             LOWER     LEVEL     UPPER    MARGINAL

JanQd         -INF       .         .      264.971
JanConvex     -INF      1.000     1.000 1.0868E+7
febQd         -INF       .         .      265.590
febconvex     -INF      1.000     1.000 9.3322E+6
marQd         -INF       .         .      265.522
marconvex     -INF      1.000     1.000 9.8584E+6
aprqd         -INF       .         .      265.522
aprconvex     -INF      1.000     1.000 9.3958E+6
mayqd         -INF       .         .      265.655
mayconvex     -INF      1.000     1.000 2.1727E+6
junqd         -INF       .         .      266.027
junconvex     -INF      1.000     1.000 2.3200E+6
julqd         -INF       .         .      266.103
julconvex     -INF      1.000     1.000 2.8894E+6
augqd         -INF       .         .      265.817
augconvex     -INF      1.000     1.000 2.8993E+6
sepqd         -INF       .         .      265.428
sepconvex     -INF      1.000     1.000 2.5180E+6
octqd         -INF       .         .      265.140
octconvex     -INF      1.000     1.000 1.1589E+7
novqd         -INF       .         .      264.958
novconvex     -INF      1.000     1.000 1.0299E+7
decqd         -INF       .         .      264.692
decconvex     -INF      1.000     1.000 1.0295E+7

---- VAR hydropower Release for Hydroelectric power generation
```

```
      LOWER     LEVEL     UPPER    MARGINAL

1       .    84437.035     +INF        .
2       .    17442.637     +INF        .
3       .    64541.405     +INF        .
4       .    1.3739E+5     +INF        .
5       .    1.2438E+5     +INF        .
6       .    1.1657E+5     +INF        .
7       .    76119.810     +INF        .
8       .    89466.344     +INF      0.002
9       .    67764.601     +INF        .
10      .    43198.672     +INF        .
11      .    66776.378     +INF     -0.005
12      .    1.5257E+5     +INF     -0.006

---- VAR bvol  Beginning Volume of Water in each month

      LOWER     LEVEL     UPPER    MARGINAL

1  6.4464E+5 6.4464E+5 6.4464E+5     0.930
2       .    6.9338E+5     +INF        .
3       .    7.7563E+5     +INF        .
4       .    8.3875E+5     +INF        .
5       .    8.3875E+5     +INF        .
6       .    8.3875E+5     +INF        .
7       .    8.3875E+5     +INF        .
8       .    8.1475E+5     +INF        .
9       .    7.4439E+5     +INF     -0.002
10      .    7.0198E+5     +INF      0.004
11      .    6.9099E+5     +INF        .
12      .    7.0942E+5     +INF        .

---- VAR Inflow of water to the lake Tenkiller in each month
(exogenously given)

      LOWER     LEVEL     UPPER    MARGINAL

1  1.3953E+5 1.3953E+5 1.3953E+5     7.331
2  1.1519E+5 1.1519E+5 1.1519E+5     7.950
3  1.3449E+5 1.3449E+5 1.3449E+5     7.882
4  1.5234E+5 1.5234E+5 1.5234E+5     7.882
5  1.4115E+5 1.4115E+5 1.4115E+5     8.015
6  1.3288E+5 1.3288E+5 1.3288E+5     8.387
7  65106.000 65106.000 65106.000     8.463
8  27618.000 27618.000 27618.000     8.167
9  35776.000 35776.000 35776.000     7.788
10 34665.000 34665.000 34665.000     7.500
11 95504.000 95504.000 95504.000     7.318
12 93730.000 93730.000 93730.000     7.052

---- VAR Lake Level in each month

      LOWER     LEVEL     UPPER    MARGINAL

1    635.000   635.000   635.000 12967.500
2    630.000   640.861   645.000       .
3    630.000   645.000   645.000  3557.364
```

```
4    630.000   645.000   645.000  9677.962
5    630.000   645.000   645.000 12865.480
6    630.000   645.000   645.000  8045.736
7    630.000   643.463   645.000      .
8    630.000   638.697   645.000      .
9    630.000   635.638   645.000      .
10   630.000   634.822   645.000      .
11   630.000   636.185   645.000      .
12   630.000   631.278   645.000      .

---- VAR Head difference between the Lake Level and the height of the
turbine

      LOWER     LEVEL     UPPER    MARGINAL

1       .      133.000     +INF       .
2       .      138.861     +INF       .
3       .      143.000     +INF       .
4       .      143.000     +INF       .
5       .      143.000     +INF       .
6       .      143.000     +INF       .
7       .      141.463     +INF       .
8       .      136.697     +INF       .
9       .      133.638     +INF       .
10      .      132.822     +INF       .
11      .      134.185     +INF       .
12      .      129.278     +INF       .

---- VAR HB  Hydroelectric power generation benefits in each months


      LOWER     LEVEL     UPPER    MARGINAL

1       .    6.1898E+5     +INF       .
2       .    1.3350E+5     +INF       .
3       .    5.0870E+5     +INF       .
4       .    1.0829E+6     +INF       .
5       .    9.9685E+5     +INF       .
6       .    9.7759E+5     +INF       .
7       .    6.4420E+5     +INF       .
8       .    7.3088E+5     +INF       .
9       .    5.2774E+5     +INF       .
10      .    3.2400E+5     +INF       .
11      .    4.8833E+5     +INF       .
12      .    1.0749E+6     +INF       .

                       LOWER     LEVEL     UPPER    MARGINAL

---- VAR hydropowe~     -INF  88843.939     +INF       .

  hydropower1  Total amount of hydropower produced in a year (12
months)in MWH

---- VAR hydro Hydropower produced in each months

      LOWER     LEVEL     UPPER    MARGINAL
```

```
1      -INF    659.223     +INF       .
2      -INF    142.180     +INF       .
3      -INF    541.779     +INF       .
4      -INF   1153.317     +INF       .
5      -INF   1044.064     +INF       .
6      -INF    978.485     +INF       .
7      -INF    632.104     +INF       .
8      -INF    717.904     +INF       .
9      -INF    531.592     +INF       .
10     -INF    336.812     +INF       .
11     -INF    525.986     +INF       .
12     -INF   1157.783     +INF       .

---- VAR Hydropower produced in each months in MWH

      LOWER     LEVEL     UPPER    MARGINAL

1   1500.000  6954.798 24500.000      .
2   1500.000  1500.000 24500.000    -3.443
3   1500.000  5715.765 24500.000      .
4   1500.000 12167.491 24500.000      .
5   1500.000 11014.875 24500.000      .
6   1500.000 10323.013 24500.000      .
7   1500.000  6668.692 24500.000      .
8   1500.000  7573.882 24500.000      .
9   1500.000  5608.300 24500.000      .
10  1500.000  3553.368 24500.000      .
11  1500.000  5549.150 24500.000      .
12  1500.000 12214.606 24500.000      .

---- VAR visit  Lake visitation in each month

      LOWER     LEVEL     UPPER    MARGINAL

1       .    1.0373E+5     +INF       .
2       .    1.0373E+5     +INF       .
3       .    1.0373E+5     +INF       .
4       .    1.8717E+5     +INF       .
5       .    2.8580E+5     +INF       .
6       .    4.2972E+5     +INF       .
7       .    3.9084E+5     +INF       .
8       .    4.3505E+5     +INF       .
9       .    2.2140E+5     +INF       .
10      .    1.0373E+5     +INF       .
11      .    1.0373E+5     +INF       .
12      .    1.0183E+5     +INF       .

                       LOWER     LEVEL     UPPER    MARGINAL

---- VAR visitors       -INF  2.5705E+6     +INF       .
---- VAR Recreatio~     -INF  1.2852E+8     +INF       .
---- VAR Hydropowe~     -INF  8.1085E+6     +INF       .
---- VAR totben         -INF  9.2627E+7     +INF       .
---- VAR RWS            -INF  8.4518E+7     +INF       .

  visitors  Total number of visitor over the year 2010
  RecreationBen  Total Recreational Benefits
```

```
    HydropowerBen  Total Hydroelectric power generation benefits
    totben  Total Benefits
    RWS  Urban & Rural Water Supply Benefits

---- VAR X  Urban & Rural Water Supply use demand in each months

           LOWER     LEVEL     UPPER    MARGINAL

jan1         .         .        +INF   -726.969
jan2         .        1.000     +INF       .
jan3         .         .        +INF  -1.427E+4
janProd      .      840.690     +INF       .
feb1         .         .        +INF   -728.411
feb2         .        1.000     +INF       .
feb3         .         .        +INF  -1.329E+4
febprod      .      721.940     +INF       .
mar1         .         .        +INF   -426.318
mar2         .        1.000     +INF       .
mar3         .         .        +INF  -1.540E+4
marprod      .      762.640     +INF       .
apr1         .         .        +INF   -738.438
apr2         .        1.000     +INF       .
apr3         .         .        +INF  -1.186E+4
aprprod      .      726.850     +INF       .
may1         .         .        +INF   -713.930
may2         .        1.000     +INF       .
may3         .         .        +INF  -1.052E+5
mayprod      .      814.980     +INF       .
jun1         .         .        +INF   -713.424
jun2         .        1.000     +INF       .
jun3         .         .        +INF  -1.151E+5
junprod      .      870.370     +INF       .
jul1         .         .        +INF   -712.920
jul2         .        1.000     +INF       .
jul3         .         .        +INF  -1.430E+5
julprod      .     1084.000     +INF       .
aug1         .         .        +INF   -713.203
aug2         .        1.000     +INF       .
aug3         .         .        +INF  -1.416E+5
augprod      .     1087.600     +INF       .
sep1         .         .        +INF   -713.858
sep2         .        1.000     +INF       .
sep3         .         .        +INF  -1.233E+5
sepprod      .      944.440     +INF       .
oct1         .         .        +INF   -725.550
oct2         .        1.000     +INF       .
oct3         .         .        +INF  -9700.585
octprod      .      896.530     +INF       .
nov1         .         .        +INF   -727.462
nov2         .        1.000     +INF       .
nov3         .         .        +INF  -5580.144
novprod      .      796.720     +INF       .
dec1         .         .        +INF   -727.748
dec2         .        1.000     +INF       .
dec3         .         .        +INF  -1.680E+4
decprod      .      796.350     +INF       .
```

```
---- VAR seepage amount of seepage in each months (exogenously given)

      LOWER     LEVEL     UPPER    MARGINAL

1   5517.000  5517.000  5517.000    -7.331
2  14776.000 14776.000 14776.000    -7.950
3   6055.000  6055.000  6055.000    -7.882
4  14218.000 14218.000 14218.000    -7.882
5  15956.000 15956.000 15956.000    -8.015
6  15446.000 15446.000 15446.000    -8.387
7  11902.000 11902.000 11902.000    -8.463
8   7433.000  7433.000  7433.000    -8.167
9   9477.000  9477.000  9477.000    -7.788
10  1557.000  1557.000  1557.000    -7.500
11  9497.000  9497.000  9497.000    -7.318
12  5149.000  5149.000  5149.000    -7.052

---- VAR release amount of water released in each months for other uses

      LOWER     LEVEL     UPPER    MARGINAL

1       .         .        +INF     -7.331
2       .         .        +INF     -7.950
3       .         .        +INF     -7.882
4       .         .        +INF     -7.882
5       .         .        +INF     -8.015
6       .         .        +INF     -8.387
7       .         .        +INF     -8.463
8       .         .        +INF     -8.167
9       .         .        +INF     -7.788
10      .         .        +INF     -7.500
11      .         .        +INF     -7.318
12      .         .        +INF     -7.052
```

APPENDIX C-- Tables

App Table C-1—Comparison Between Historical Lake Level Vs Optimal Lake Level When Recreational Benefits Were And Were Not Included In The Objective Function

Month	Historical Lake Level*	Lake Level Without Recreation*	Lake Level With Recreation*
Jan	632	635	635
Feb	632	641	641
Mar	633	645	645
Apr	633	645	645
May	634	645	645
Jun	635	645	633
Jul	634	643	632
Aug	630	639	632
Sep	628	636	632
Oct	628	635	632
Nov	630	636	635
Dec	631	631	631

**in Feet*

App Table C-2—Comparison Between Historical Lake Volume Vs Optimal Lake Volume When Recreational Benefits Were And Were Not Included In The Objective Function

Month	Historical Lake Volume *	Lake Volume with Recreation*	Lake Volume without Recreation*
Jan	644,640.00	644,640.00	644,640.00
Feb	653,160.00	693,380.00	693,380.00
Mar	661,220.00	775,630.00	775,630.00
Apr	664,810.00	838,750.00	838,750.00
May	672,480.00	838,750.00	838,750.00
Jun	679,640.00	838,750.00	838,750.00
Jul	703,580.00	663,390.00	838,750.00
Aug	631,730.00	654,330.00	814,750.00
Sep	594,680.00	653,920.00	744,390.00
Oct	596,120.00	653,910.00	701,980.00
Nov	596,290.00	654,500.00	690,990.00
Dec	625,240.00	691,610.00	709,420.00

**in Acre Feet*

App Table C-3—Comparison Between Historical Releases For Hydropower Generation Vs Optimal Hydropower Generation Releases When Recreational Benefits Were And Were Not Included In The Objective Function

Month	Historical Hydropower Generation Releases*	Optimal Hydropower Generation Releases with Recreation*	Optimal Hydropower Generation Releases without Recreation*
Jan	86,551.00	84,437.04	84,437.04
Feb	82,287.00	17,442.64	17,442.64
Mar	100,300.00	64,541.41	64,541.41
Apr	104,360.00	137,390.00	137,390.00
May	86,434.00	174,580.00	124,380.00
Jun	70,359.00	240,000.00	116,570.00
Jul	83,979.00	63,004.90	76,119.81
Aug	53,020.00	19,417.79	89,466.34
Sep	21,650.00	25,355.36	67,764.60
Oct	29,806.00	18,481.17	43,198.67
Nov	49,364.00	54,731.17	66,776.38
Dec	75,611.00	141,260.00	152,570.00
Total	843,721.00	1,040,641.45	1,040,656.88

**in Acre Feet*

App Table C-4—Comparison Between Hydroelectric Power Generation Benefits When Recreational Benefits Were And Were Not Included In The Objective Function

Month	Hydropower Benefit with Recreation	Hydropower Benefit without Recreation
Jan	$618,980.00	$618,980.00
Feb	$133,500.00	$133,500.00
Mar	$508,700.00	$508,700.00
Apr	$1,082,900.00	$1,082,900.00
May	$1,367,300.00	$996,850.00
Jun	$1,842,000.00	$977,590.00
Jul	$490,090.00	$644,200.00
Aug	$150,860.00	$730,880.00
Sep	$192,090.00	$527,740.00
Oct	$136,770.00	$324,000.00
Nov	$397,760.00	$488,330.00
Dec	$995,250.00	$1,074,900.00
Total	$7,916,200.00	$8,108,570.00

**in US $*

App Table C-5—Comparison Between Lake Recreational Benefits When Recreational Values Were And Were Not Included In The Objective Function

Month	Lake Recreational Benefits With Recreation	Lake Recreational Benefits Without Recreation
Jan	$5,186,500.00	$5,186,500.00
Feb	$5,186,500.00	$5,186,500.00
Mar	$5,186,500.00	$5,186,500.00
Apr	$9,358,500.00	$9,358,500.00
May	$14,290,000.00	$14,290,000.00
Jun	$23,622,500.00	$21,486,000.00
Jul	$26,585,000.00	$19,542,000.00
Aug	$22,322,000.00	$21,752,500.00
Sep	$11,070,000.00	$11,070,000.00
Oct	$5,186,500.00	$5,186,500.00
Nov	$5,186,500.00	$5,186,500.00
Dec	$5,091,500.00	$5,091,500.00
Total	$138,272,000.00	$128,523,000.00

VITA

Deepayan Debnath

Candidate for the Degree of

Master of Science or Arts

Thesis: OPTIMAL ALLOCATION OF RESERVOIR WATER: A CASE STUDY OF LAKE TENKILLER

Major Field: Agricultural Economics

Biographical:

Personal Data: Born in a small village of West Bengal, India on November 7th 1980. Son of Mr. Nityananda Debnath and Mrs. Saraswati Debnath.

Education:Bachelors of Arts and Master of Arts from Kalyani University, West Bengal, India and completed the requirements for the Master of Science in Agricultural Economics at Oklahoma State University, Stillwater, Oklahoma in December, 2009.

Experience:Worked in an Agri-based industry for almost one year and worked as a faculty in a high school for eight month. Now working as a Graduate Research Assistant in the Department of Agricultural Economics at Oklahoma State University from November 2007.

Professional Memberships: Southern Agricultural Economic Association (SAEA).

Name: Deepayan Debnath Date of Degree: December, 2009

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: OPTIMAL ALLOCATION OF RESERVOIR WATER: A CASE STUDY OF LAKE TENKILLER

Pages in Study: 101 Candidate for the Degree of Master of Science

Major Field: Agricultural Economics

Scope and Method of Study: The purpose of this research study is to determine the optimal allocation of reservoir water among consumptive and non-consumptive uses. Hydroelectric power generation benefits and lake recreational benefits (non-consumptive uses) and urban and rural water supply benefits (consumptive uses) are implicitly considered in this study. Recreational benefits depend explicitly on the summer lake levels, while the flood control capacity of the reservoir is maintained through upper bounds on the lake level. An optimization model using non-linear programming is developed to optimally allocate reservoir water among competing uses. General Algebraic Modeling System (GAMS) with MINOS solver is used to solve this model. Lake Tenkiller and its surrounding area of northeastern Oklahoma are considered for this study. A mass balance equation is used to determine the level and volume of water in the lake for each month over twelve month period. This paper compares different water management scenarios, (recreational benefits are and are not included in the objective function) while managing Lake Tenkiller.

Findings and Conclusions: The results of this study showed that the total benefits arising from the use of Lake Tenkiller water will increase under the optimization model compare to the benefits obtained under historical releases. It was also found that when recreational benefits are included within in the objective function then the total benefits will be greater than when the recreational benefits are not included in the objective function. The results also showed that for Lake Tenkiller maintaining lake level around the normal lake level of 632 feet during summer months and shifting the releases for hydropower generation to other months increased overall benefits including recreational benefits with only a slight reduction in hydropower generation values. Therefore for Lake Tenkiller, it is beneficial to maintain lake levels near the normal pool of 632 feet during the summer months in order to maximize the net social benefits. It was shown that for Lake Tenkiller an optimal allocation of water between competing uses requires that the marginal price of water at the lake in each month must be same for the last unit of water used for hydropower, recreation or urban and rural water uses.

ADVISER'S APPROVAL: Dr Arthur Stoecker