Optimal Allocation of Reservoir Water

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Abstract

The purpose of this paper is to determine the optimal allocation of reservoir water among consumptive and non-consumptive uses. A non-linear mathematical programming model is developed to optimally allocate Lake Tenkiller water among competing uses that maximize the net social benefit. A mass balance equation is used to determine the level and volume of water in the lake. This paper examines the effect of water management on lake resources when recreational values are and are not included as control variables in the optimization process. Results show that maintaining lake level near 'normal lake level' of 632 feet during the summer months and shifting releases for hydropower generation to other months increased overall benefits including recreational benefits with only a slight reduction in hydropower generation.

Key words: consumptive and non-consumptive use, mass balance equation, non-linear mathematical programming, optimization, recreational uses, water allocation

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INTRODUCTION

The scarcity of water resources is one of the most pervasive natural resource allocation problems facing by the water users and policy makers. Water scarcity has become an important constraint on economic development. This has resulted in fierce competition for water resources between economic sectors that rely upon it (Winpenny, 1994). With the growth in population and income, the demand for water for both consumptive and non-consumptive use increases. That results in increased competition and conflict among different water users. In future, balancing water demand with available water supply will become more difficult with gradual impact of growth and increasing recreational demand. Thus a big challenge for the policy maker is in addressing the water management issue. In the context of water management, decision makers in the arid and semi-arid states face questions about how much water should be allocated among competing uses such as hydroelectric power generation and municipal and industrial water supply versus how much water should be maintain in the lake for recreational purposes.

The problem of resource allocation is more complicated since in case of water markets for all uses may not be present and/or may not operate efficiently. Many people intuitively reject pricing of a resource (water) that is necessary for life. According to the FAO (1954) some Islamic cultures or religions prohibit allocation of water rights by market forces. Thus a water allocation model that considers both market and non-market benefits is required if a particular reservoir is to be managed to maximize net social benefit.

A reservoir may be managed with respect to hydropower generation, flood control, irrigation and water supply uses while recreational uses are often treated as residual. Though water use for recreation and hydropower is non-consumptive, it may be sensitive to lake level while water releases for municipal and rural water supply is a consumptive use. The question is "What tradeoffs between consumptive and non-consumptive uses are necessary in order to maximize net social benefits?"

Oklahoma requires an effective and comprehensive plan to meet the future water supply challenges. Thus, a water management plan is required to serve as a guide for the Oklahoma Water Resource Board (OWRB) and other state agencies to assure a safe and reliable supply of water to meet both the consumptive and non-consumptive needs of all Oklahomans for the next 50 years.

PREVIOUS STUDIES

Water allocation has received considerable attention in the recent past by the scientific community. Bielsa and Duarte (2001), Qubáa et al. (2002) and Chatterjee, Howitt and Sexton discussed the optimal allocation of water between market uses but did not directly consider management to maximize benefits from the distribution of water among consumptive and non-consumptive uses. Mckenzie (2003) developed a model of 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. Wurbs (1997) discussed the multiple beneficial uses of reservoir storage such as municipal and industrial water supply, irrigation, hydroelectric power generation, and navigation. However this paper did not discuss how to manage the multiple uses of a reservoir that will maximize net social benefits.

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 released for hydropower generation yielded higher benefits than managing lake volumes for recreation.

This study develops an optimization model that will maximize net social benefits for hydropower generation, municipal and water supply and recreational uses subject to maintaining capacity for flood control and releases to meet downstream needs.

DATA

Tenkiller Ferry Lake of northeastern Oklahoma has 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). The USACE also provided monthly visitor data for the same period. Monthly electrical prices were obtained from the U.S. Department of Energy Information website. Data concerning the municipal and 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 EPANET water simulation models for 15 communities' water systems that were using Lake Tenkiller water. Finally, survey data (Boyer et al. 2008) were used to apply recreational values to visitor numbers according to the lake level.

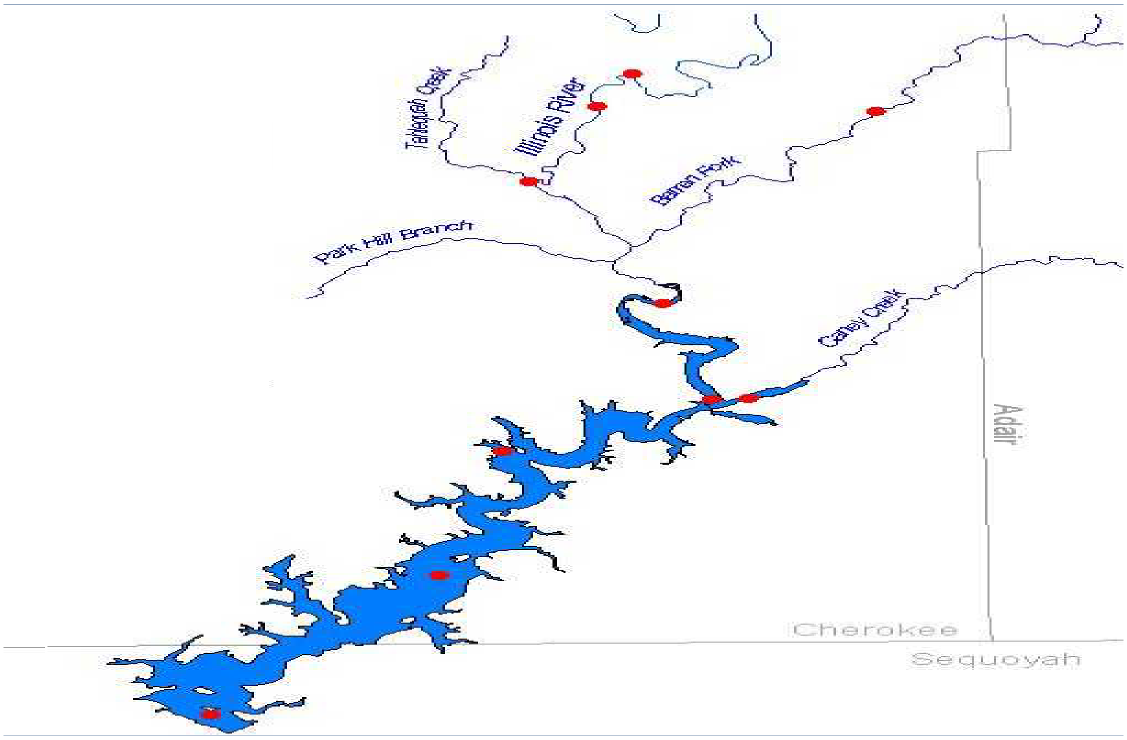

Figure 1. Tenkiller Ferry Lake

MODEL

In this analysis, three different types of reservoir water uses are considered while the flood control benefit is implicitly addressed by maintaining a maximum volume of water in each month that represents the reservoir capacity to capture possible floodwater. The municipal and rural water supply is consumptive use while hydroelectric power generation and lake recreational values are non-consumptive uses which compete among each other. An optimization model is developed that considers the tradeoff between hydropower generation and lake recreational benefits when allocating the reservoir water.

The overall objective of this study is to determine the optimal allocation of reservoir water among consumptive (municipal and rural water supply) and non-consumptive (hydroelectric power generation recreational and lake recreational values) uses that maximize the net social benefits and to include the value of the lake recreation as an explicit variable while determining the optimal lake use. The specific objectives of the model are to determine optimal monthly lake levels and releases to maximize net social benefits from:

a. Hydropower generation,
b. Lake Recreational Use, and
c. Municipal and Rural Water Supply while,
d. Maintaining capacity for flood control, and
e. Minimum releases for downstream needs.

A deterministic non-linear programming model was constructed to find the optimal allocation of reservoir water among competing uses based on inflows, water rights, demands for hydroelectricity and recreational uses over the different months of a year. It consists of a twelve month time horizon from January to December. The model uses a mass balance equation that determines the level and volume of water in the lake by equating the inflows and outflows in each period. The top of the flood control pool was 667 feet above sea level (FASL). The maximum lake level was constrained to be less than 645 feet above sea level (FASL) to maintain flood control capacity of the reservoir.

The optimization model maximizes the sum of net monthly social benefit arising from hydroelectric power generation, municipal and rural water supply and lake recreation are specified as:

Maximize:

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

Subject to

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

$$\text{Volume}_\text{m} \geq \text{Volume}_{min}$$

$$\text{Volume}_\text{m} \leq \text{Volume}_{max}$$

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

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

A simple double log regression model was used to calculate the volume (acre ft) of water in the reservoir given the lake level (feet). The estimated equation is:

$$\underset{}{\text{Ln(Volume in acre ft)}} = \underset{(-2535)}{-66.485} + \underset{(3045)}{12.386}\text{Ln(Lake Level in ft)}$$

$R^2 = 0.99$ with 4532 observations, t-values are in parenthesis

After taking the antilog, the volume equation was obtained as:

$$\text{Volume(acre ft)} = V_0 * L^{12.386}$$

Where,

$V_0 = e^{-66.485}$ and L = Lake level (above sea level)

The mass balance equation used to determine the volume of water in each month is specified as follows:

Beginning Balance + Inflow + Rainfall = Evaporation + Release for power + Other Release + Ending Balance.

The economic benefit arising from hydroelectric power production was obtained by multiplying the amount of electricity produced in a particular month to the price of electricity ($0.09 per kwh) obtained from U.S government energy statistics. ReVelle (1999) presents the formula for power generation as a nonlinear function depending on the product of release and head measured in feet above the turbine. The function can be expressed as:

$$KW_m = aR_mH_m$$

Where,

KW_m = amount of electricity produced (kwh) 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 in month m*

*the head was calculated as $(\text{level}_m + \text{level}_{m+1})/2 - 486.52$. The height of the top of turbine was given as 486.52 feet above the sea level.

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 is as follows:

$$\begin{array}{ll} KW_m = 0.232457\text{Head}_m\text{* Released}_m\text{ (acr feet)} & \\ \qquad (1152) & \text{R-Square} = 0.99 \end{array}$$

*t-value is in parenthesis

Lake recreation benefits depend on the lake level. The effect of varying lake levels on the visitor attendance was estimated by regressing the number of monthly visitors against the lake level for the same month. The estimated regression equation used in this study was:

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

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

$$\begin{array}{llll} -254\ Lv_{Jn}^{2*} & -1072\ Lv_{Jly}^{2*} & -\ 254\ Lv_{Aug}^{2*}, & r^2 = 0.66 \\ (-1.95) & (-2.51) & (-1.95) & \end{array}$$

*Variables significant at 10 percent level or less, t-values are in parentheses

- The variables Apr, May, June, July, Aug and Sep are 0-1 dummy variables which are 1 in the indicated months and zero otherwise.
- Tsumr is a time (2000 = 0) trend for months June, July, and August. The other months were not found to significantly vary with time.
- ALkLv is the Average monthly lake level – 632 (normal lake level).
- LvJun is a discrete variable to test if visits to the lake in June are more sensitive to lake levels than in other months.
- Lv_{Jn}^2 is the square of the June lake level – 632, $= [\text{Lake level} - 632]^2$
- Lv_{Jly}^2 is the square of the July lake level – 632, $= [\text{Lake level} - 632]^2$, and
- Lv_{Aug}^2 is is the square of the August lake level – 632, $= [\text{Lake level} - 632]^2$.

The recreational value of Lake Tenkiller was as estimated as part of a larger random utility travel cost model for all lakes in Oklahoma by Dr Tracy Boyer. 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 analysis, the value of a visitor day at normal lake levels was placed at only \$50 per day. This is a conservative value, well below the estimated value of \$191 per day. The study by Roberts et al. (2006) had shown the willingness to pay for a visitor day declined by \$0.82 for each foot the lake was below the normal level of 632 ft. The lowest level tested was 624 feet. The value of a visitor day used in this model was taken to be:

\$50 per day if the lake level $\geq$ 632 feet,

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

\$43 per day if the lake level is $\leq$ 624 feet.

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).

The benefits arising from the municipal and rural water supply were calculated as the net social welfare (summation of consumer surplus and producer surplus) derived from water use. The benefits accruing from rural water supply were calculated using simple arithmetic by adding the consumer surplus (CS) and the producer surplus (PS).

The net benefits arising from the municipal and industrial water supply were determined as:

$$NSB_m = (d_{0m}Q_m + 0.5d_{1m}Q_m^2) - (c_0 + c_1Q_m)$$

The first part of the above equation was obtained by integrating over the linear demand function: $P_m = d_{0m} + d_{1m}Q_{m,}$

Where, $d_{0m} = P_m - d_{1m}Q_m$, $d_{1m} = (P_m/Q_m)*1/\rho$

Price Elasticity: $\rho = (dq/dp)(p_m/q_m)$

The value of d_{0m}, d_{1m} and Q_m was determined from the following tables. The estimated amount of water used per day by each municipal and rural water system was shown below in Table 1.

Table 1. Actual and Projected Water Demands by User Based on Projections by the US Army Corps of Engineers.

Year	2000	2010	2020	2030	2040	2050	2060
		(Thousand gallons per day)					
Muskogee RWD#4	74	82	85	88	93	97	105
Lost City RWD_RWD11	215	239	248	255	269	282	303
Cherokee RW 1	75	84	87	89	94	99	106
Muskogee RWD#7	144	160	166	171	180	189	203
Cherokee RW 8	108	119	124	128	134	141	152
Cherokee RW 7	108	119	124	128	134	141	152
Cherokee RW 3	189	209	217	223	235	247	265
Tahlequah Water	653	722	760	792	841	900	955
Stick Ross Mt. Water System	215	239	248	255	269	282	303
Cherokee RW2	86	95	99	102	107	113	121
LRED east	61	68	71	73	77	81	87
Summit Water	72	80	83	86	90	94	101
Cherokee RW13	75	84	87	89	94	99	106
LRED east	47	53	55	56	59	62	67
Tenkiller State Park	19	21	22	23	24	25	27
Sequoyah WW	1492	1653	1714	1768	1859	1951	2098
LRED west	59	66	68	70	74	77	83
Burnt Cabin	32	36	37	38	40	42	45
Lake Tenkiller Harbor	32	36	37	38	40	42	45
Fin & Feather Water	38	42	43	45	47	49	53
Paradise Hills	24	26	27	28	30	31	33
Tenkiller Aqua Park	11	12	12	13	13	14	15
Vian	194	215	223	230	242	254	273
Gore	292	323	335	346	364	382	411
East Central OK	205	227	235	242	255	268	288
Total	4520	5010	5207	5376	5664	5962	6397

The data in Table 1 differ from those in the USACE 2001 in that projections were made for 2060 and because demands for Sallisaw, Muldrow, and Roland were deleted.

A series of monthly water demands were derived based on precipitation and temperature elasticities obtained from another water demand simulation program IWRMAIN developed by Davis et al. (1987) for the USACE. Since the area was mostly residential the single family dwelling elasticities were used. The elasticities used for each month along with the average monthly temperature and precipitation data for the area were given below in Table 2. The USACE conducted a study of providing wholesale water to cities and rural water districts to the northwest and to the east of Lake Tenkiller. They estimated the cost of supplying water to some thirty cities and rural water systems at \$2.25 per thousand gallons. We use this price in calculating the d_{1m}.

Table 2. Average Monthly Temperature and Precipitation Values and Elasticities Used to Derive Monthly Water Demands for the Tenkiller Study Area.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall (in)	2.4	2.4	4.2	4.1	5.7	5.2	3.5	3.2	5.3	4.3	4.7	3.2
Temperature (F)	36.8	42.4	51.5	60.3	67.9	75.6	80.4	80	72.4	61.7	49.5	39.9
Rainfall Elasticity	-0.25	-0.25	-0.25	-0.25	-0.02	-0.02	-0.02	-0.02	-0.02	-0.25	-0.25	-0.25
Temp Elasticity	0.45	0.45	0.45	0.45	1.5	1.5	1.5	1.5	1.5	0.45	0.45	0.45
Price Elasticity	-0.04	-0.04	-0.04	-0.04	-0.25	-0.25	-0.25	-0.25	-0.25	-0.04	-0.04	-0.04

Source: IWR Main Davis et al. 1987

The second part is the cost function:

$$\text{Cost} = c_0 + c_1 Q_m$$

A hydraulic 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. The EPANET software was used to run this simulation model while the pipelines 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:

$$\underset{}{\mathrm{Cost}_m} = \underset{(2.5)}{-458} + \underset{(760)}{257.64\mathrm{AF}_m} \qquad R^2 = 0.99$$

* t-values are in parenthesis

Where,

Cost_m = total pumping cost in month m

AF_m =amount of water pumped in month m (acr ft)

A flowchart representing the net social benefits arising from different uses is shown in Figure 2. As shown in the schematic representation, the total inflow of the water is distributed among consumptive and non-consumptive uses. The non-consumptive uses were further sub-divided into non-market lake recreation 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 and the benefits arising from municipal and rural water supply use depend on the amount of water released for each purpose. The hydroelectric power generation benefits were also depends on the effective head of the turbine which was derived from lake elevation and the height of the top of the turbine.

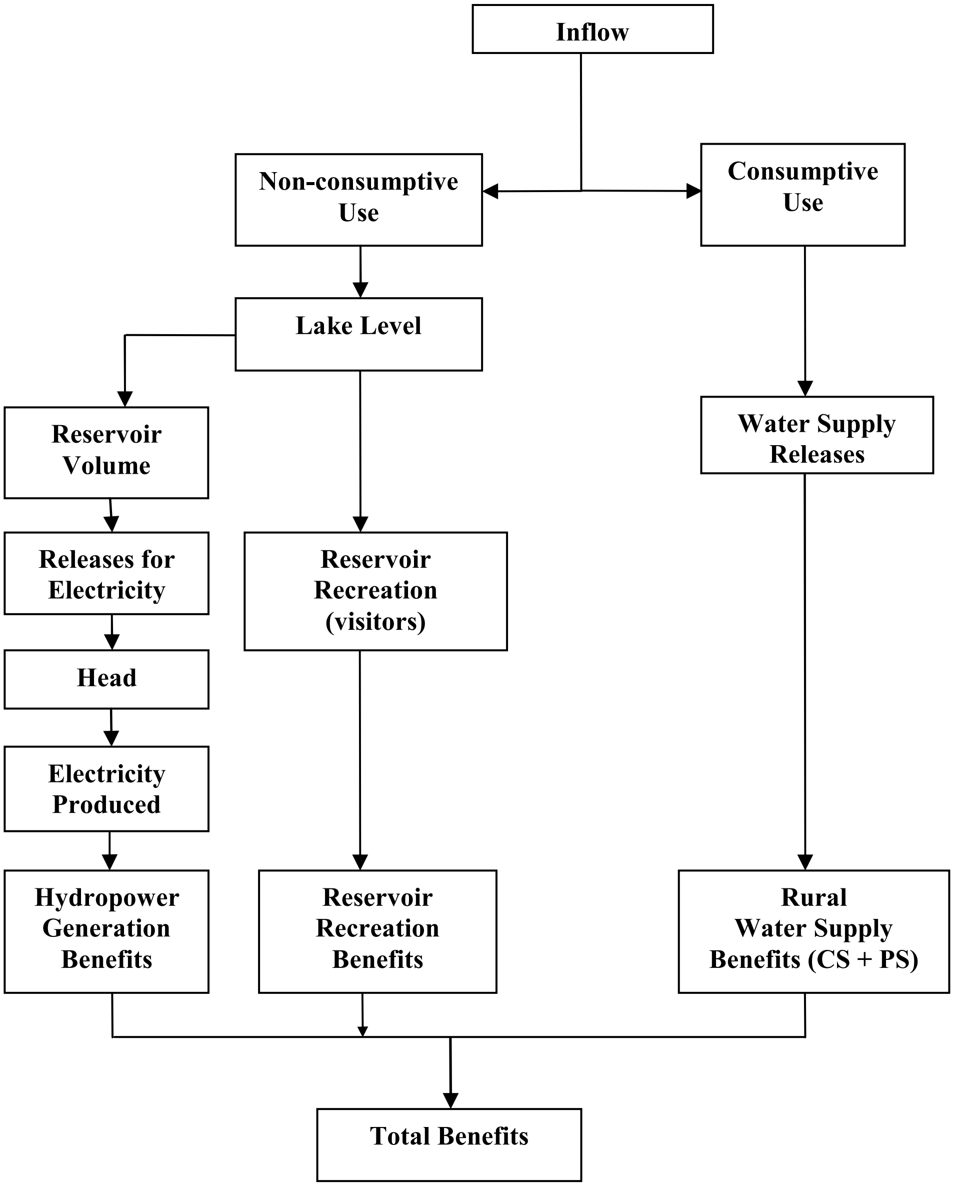

Figure 2. Flowchart Illustrating the Model

RESULTS

The model was solved for the years 2010, 2020, 2030, 2040, 2050, and 2060. The values for years between the dates were determined by interpolation. The NPV was determined by discounting over the 50 year period at 4.875 percent. This was the discount rate designated by the Water Resources Council for water projects in 2008.

The 50 year discounted value of net social benefits when lake recreation was not directly included in the objective function was \$ 3,338,746. In this case of Lake Tenkiller, water was optimally allocated among hydroelectric power generation and municipal and rural water supply. When recreational uses were included in the objective function, total net benefits were increased to \$ 3,399,821 mainly due to the gain from the recreational benefits during the summer months when most of the people choose to visit the lake. These results are shown in Table 3.

Table 3. Comparison of the NPV of Benefits from 2010 to 2060 from LakeTenkiller when Recreational Values are Not Included and When Recreational Values are Directly Included in the Objective Function (Values in thousand dollars)*

Recreational Values Post Solution		Recreational Values in Objective Function	
Item	Value	Item	Value
Power Generation	$ 16,120	Power Generation	$ 15,536
Municipal	900,180	Municipal	873,618
		Recreation	2,510,667
Objective Function	916,300	Objective Function	3,399,821
Recreation	2,422,446		
Total All Values	$3,338,746	Total All Values	$ 3,399,821

*Recreation valued at \$50 per visitor day. Values were discounted at 4.875 percent.

The results are of particular interest since neither municipal & rural water supply nor recreations were considered as primary uses when the reservoir was built.

It shows that when recreational benefits were directly included in the objective function, there was a discounted gain of nearly 61 million dollars of additional value from the lake resource over the 50 year period. When the recreational visitor day was valued at $50, the total recreation values were much larger than the values for power generation and municipal & rural water supply use. With the recreation values at $50 per visitor day, there was an additional 88 million dollars in recreational benefits derived by maintaining the lake level at slightly above 632 feet during the summer months and shifting releases for power generation away from summer months.

The tradeoff between lowering the lake level for hydropower production and maintaining the lake level for recreation is discussed below. The results in Table 4 show that during the summer months of June, July or August, a one foot reduction in the lake level from the ‘normal level’ of 632 feet would cause a loss of recreational benefits of $3.2, 3.4 or $1.8 million in June, July or August respectively. However if the water were used for hydropower, it would only generate electricity worth $39 thousand. The value of electricity is based on the average monthly price of $ 0.09 per kwh. The price for electricity would be higher if sold at peak prices or if the values of carbon avoided were added on.

The result shows that the opportunity cost of recreational values forgone may exceed the value of electricity generated differ from the results obtained by Ward et al. (1996) for reservoirs in New Mexico. This is in part because the number of monthly summer visitors to Lake Tenkiller varies between 400-over 500 thousand and in part because the amount of head above the turbines is lower for Lake Tenkiller.

Table 4. 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 (1000 acr ft)	Release (1000 acr ft)	Hydropower Produced (1000 Kwh)	Hydropower Value Gain ($1000)
632	654	13	430	34
631	641			

Loss in recreational benefits by reducing the lake level by 1 foot during the summer months

Month	Lake Level (feet)*	Estimated Visits (1000)	Recreation Benefit ($1000)	Recreational Value Loss ($1000)
May	632	286	14288	1882
	631	283	12406	
Jun	632	467	23371	3245
	631	459	20126	
July	632	532	26585	3449
	631	528	23136	
August	632	446	22322	2886
	631	444	19436	

*feet above sea level

During the month of July, when the number of visitors was at its peak the reduction of lake level by one foot would increase the generate electricity worth $ 39,000 while recreational benefits would decline by $ 3,449,000 due to an estimated decrease in the number of visitors by 4,000 and the value of visitor day decrease to $ 43.82. This clearly shows that during the summer months maintaining near 'normal lake level' for recreation outweighs the reductions in electricity generated.

The average operating levels from 1990 through 2006 (Figure 3) are compared with the derived optimal operating levels if the lake were operated to maximize power and municipal & rural water supply benefits (with lake levels simply constrained between 620 and 645 feet) and when recreational benefits were included in the objective function. If the lake were managed to maximize hydropower production, it would be optimal to increase the lake levels for maximum head above the turbines and release water during the peak average price months of June – August. When recreational values were considered, the optimal summer lake level should not be more than five feet above the normal level. This is because lake levels above the normal level of 632 feet would reduce visits in the month of June, July, and August. And the levels are also above the historical levels in part because expected municipal & rural water supply values in 2010 are greater than historical levels. The USACE may also be operating the lake to avoid large changes in the water levels which hamper marina and boat dock operations, Badger (1975).

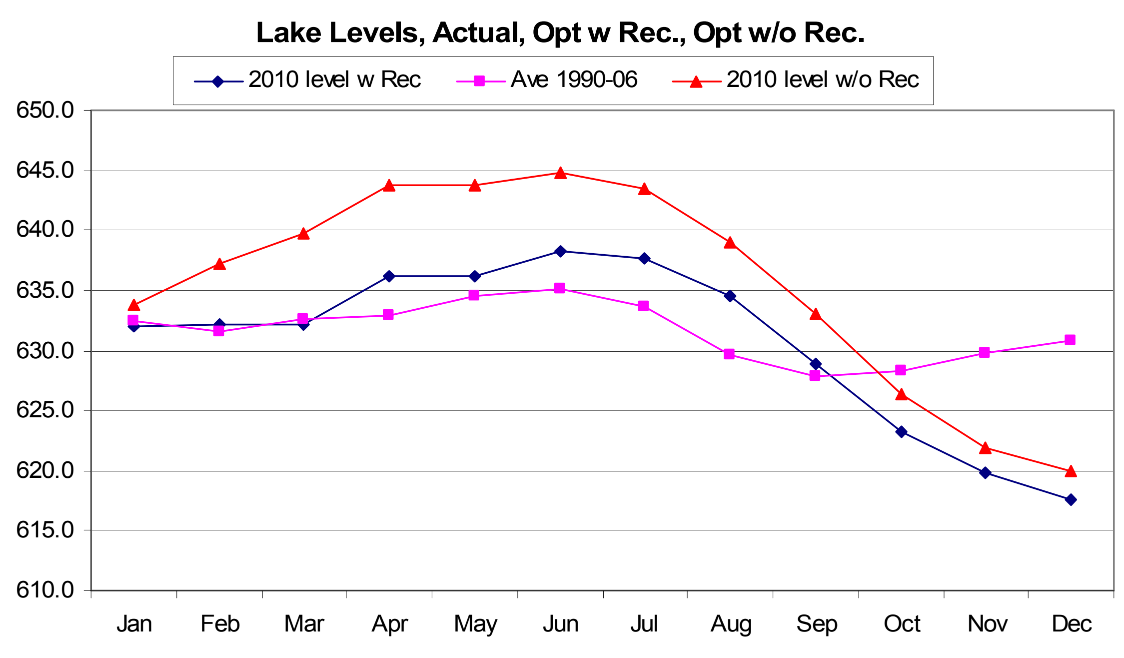

Figure 3. Comparison of Average Monthly Levels for Lake Tenkiller from 1990-2006 with Optimal Levels for 2010 when Recreational Values Are and Are Not Directly Included in the Optimization.

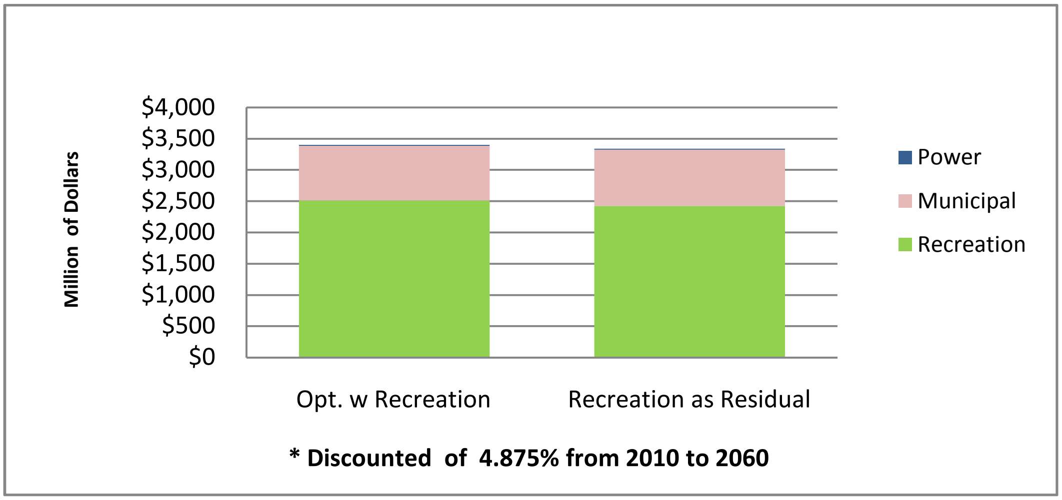

Figure 4. Comparison in Net Present Value of Services from Lake Tenkiller when Recreation Values are Directly Included in the Optimization, (Recreation Valued at $50)

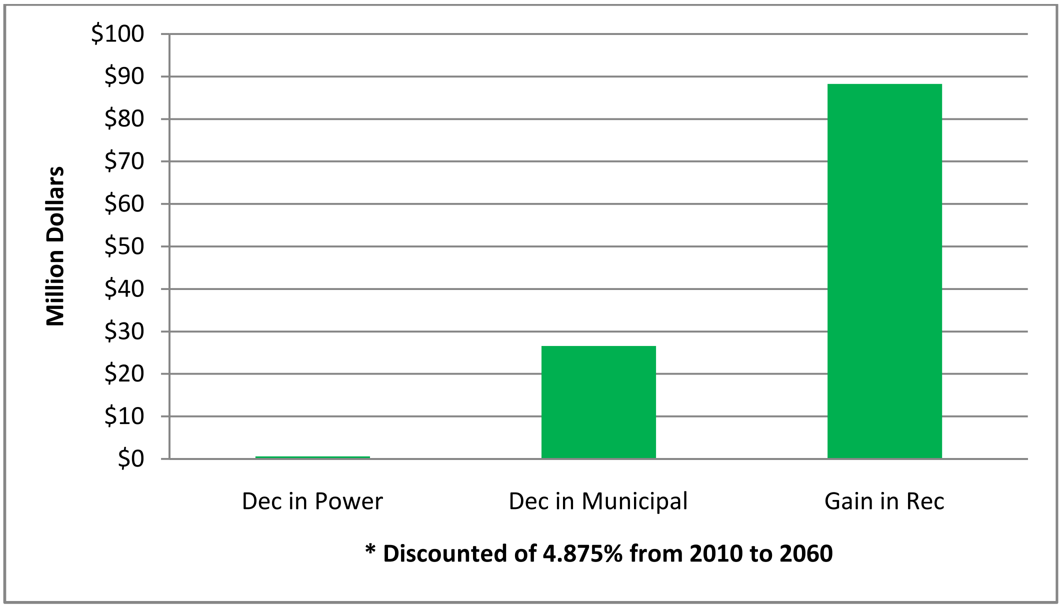

Figure 5. Tradeoff in the Net Present Value between Power and Recreation Values when Recreation Values are Included in the Objective Function of the Optimization Model.

The change in the Net Present Value when the recreational benefits are and are not included in the optimization model is shown is the Figure 4. While, Figure 5. represents the aggregate tradeoff between power generation and recreation values when recreational benefits are included in the model.

CONCLUSIONS

This optimization model shows that the net social benefit can be explicitly increased by considering both market and non-market uses when allocating water from Lake Tenkiller. It also shows that the greatest changes in the resource allocation are in the timing of releases for power generation and the resulting effect on recreation visitors. That model tends to maximize benefits arising from recreational uses by maintaining lake level slightly above the 'normal lake level' of 632 feet above sea level.

This study shows that during the summer months, the gain arising from recreational benefits is much higher than the hydroelectricity production benefits. The results show that during the summer months the visitors are sensitive to the lake levels that are both above and below an optimum level. For this lake it appears that additional recreational values are more valuable than additional hydroelectricity generated during the summer months of June, July, and August. Therefore the lake level during these months should be maintained slightly above the normal pool level of 632 foot to maximize net social benefits.

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