Integrated Reservoir Management under Stochastic Conditions

Deepayan Debnath, Art Stoecker, Tracy Boyer, and Larry Sanders;
Department of Agricultural Economics, Oklahoma State University
Stillwater, Oklahoma 74078

Selected paper prepared for presentation at the 2011 Joint Annual Meeting
Western Agricultural and Resource Economics Association and
Canadian Agricultural Economics Society
Bnaff, Alberta, June 29-July 1, 2011

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Deepayan Debnath[1], Art Stoecker[2], Tracy Boyer[3], Larry Sanders[3]

Abstract

This study is primarily concerned with the planning and management of a multipurpose reservoir. An economic optimization model using non-linear programming is developed and solved using Risk Solver to maximize the net economic benefits derived from different use of reservoir water under uncertainties. Marketed: urban and rural water supply and hydropower generation and non-marketed: lake recreation uses are considered directly in the maximization problem while flood control and downstream releases are incorporated as constraints. Stochastic inflows to the reservoir are considered to be log normally distributed. Lake Tenkiller because of its clear water and scenic beauty is chosen for this study. A mass balance equation is used to determine the level and volume of water in the lake for each period over the year 2010. Both the value of a visitor day and the number of visitor are the function of lake level which makes it completely unique. Results show that for Lake Tenkiller it is beneficial to maintain the lake level at around 634 feet above mean sea level (famsl) until mid-August, and then start drawing down for hydropower generation. A sensitivity analysis is also performed with different values of visitor day and peak electricity prices. However, the results remain the same for all different scenarios making the model completely robust and the solution also satisfies the equi-marginal principle.

Key words: Economic optimization, Lake levels, Marketed and non-marketed water uses, Non-linear programming, Recreational benefits, Reservoir management, Stochastic inflows, Value of a visitor day

Deepayan Debnath, PhD candidate; Dr Art Stoecker, associate professor; Dr. Tracy Boyer, associate professor; and Dr. Larry Sanders, professor, Department of Agricultural Economics, Oklahoma State University.

Introduction

In the last fifty years reservoir water uses have subsequently changes from flood control and hydropower generation to in-stream and down-stream recreation and municipal and industrial water supply, mainly because of rapid growth in population and income. People now spend a considerable amount of money on recreational activities such as skiing, hiking, boating, fishing and, etc. Therefore, valuing non market good such as recreational uses and including it in the management of a multipurpose reservoir is become essential. Often there are conflicts among these competing uses, and it is even more complex in the absence of formal market. These make the operation, management, and planning of a multipurpose reservoir very complicated and difficult. The problem becomes more complicated due to the stochastic nature of the inflows, and sometimes these reservoirs are older than fifty years, which are above the normal life of a dam that forced the reservoir to be managed way below the flood-control conservation pool.

Recently, there was a conflict between the state of Georgia, and Florida over the allocation of Lake Lanier water, which is the primary source of water to the city of Atlanta and supplies water to Florida's Apalachicola River where two species of mussel are federally-protected, even though the lake was initially built for hydropower production (Serrie J. 2009). The problem is also persistent in the state of Oklahoma where many of its lakes are popular for recreational uses, unfortunately until now the comprehensive water plan (OWRB, 2008) has ignored the non-market uses while managing the lake.

The major contribution made in this paper is the development of a stochastic non-linear optimization model maximizing the net social economic benefits derived from hydropower generation, recreational uses, and municipal and industrial uses, the model also considers the flood- control capacity and downstream releases by imposing bounds.

Optimization models that partially address the problem of surface water allocation have been employed for several decades. Ward and Lynch (1996) used an integrated optimal control model to evaluate the allocation of New Mexico's Rio Champa basin water between lake recreation, in-stream recreation, and hydroelectric power generation. The authors found that water released for hydropower generation yielded higher benefits than managing lake volumes for recreational uses. Chatterjee et al. (1998) determined the optimal release pattern of reservoir water for irrigation and hydropower production in the western United States. They showed water should be released if the value of releasing water for hydropower generation and irrigation is higher than the value of storing water for other purposes. Hanson et al. (2002) describe how the reservoir recreational values changed with the lake level. They used contingent valuation to estimate the impact of water level changes on recreational values. They found that during the summer months when the recreational benefits are valued most, higher lake levels should be maintained. Changchit and Terrell (1993) used the chance-constrained goal programming (CCGP) concept to solve the problem of multiobjective reservoir operation under stochastic inflows. In their model, water supply for municipal and industrial and downstream water supply was given the top priority, and the excess amount of water was released through the turbine to generate hydropower that differs from the current study. However, these studies do not simultaneously consider marketed (hydropower generation, municipal and industrial water use, irrigation and other uses) and non-marketed recreational values in reservoir management under uncertainty.

The present study will show that in summer when the number of visitor depends on the lake level, a tradeoff occurs between hydropower generation values and the recreational values that make it different from all other existing literature on reservoir management. This research is unique since it considers the economic benefits derived from hydropower generation, recreational, municipal and industrial use, flood control level and downstream releases in a single model, while inflows are considered to be stochastic.

The main objectives of this study are, given stochastic inflows to the reservoir, to (1) determine the average monthly lake level and release pattern of water from the reservoir that would maximize the net total economic benefits, (2) compare the changes in the economic benefits and lake levels between cases when recreational values are directly included in the objective function as opposed to cases where recreation values are calculated after the optimization, (3) determine the sensitivity of optimal lake levels to changes in the value of electricity prices and the value of a visitor day, and (4) compare the economic benefits derived under stochastic and deterministic condition versus the economic benefits obtained based on historically managed lake levels and releases.

Study site

In 1953, the United States Army Corps of Engineers (USACE) completed the construction of the Tenkiller Ferry dam on the Illinois River in northeastern Oklahoma for the purposes of flood control and hydropower generation. However, Lake Tenkiller has become one of the most popular recreation lakes in Oklahoma (USACE 2009). According to USACE, it is one of the finest lakes in Oklahoma. Because of its clean water and abundant recreation facilities, it is very popular among visitors. It has water related recreational activities such as skiing, hiking, sailing, and fishing. With a depth of 165 feet and clear water, it is also very popular among scuba divers. It has a shoreline of about 130 miles and a surface area of 12,650 acres. The total volume of water in the lake is 654,231 acre-feet at the normal lake level of 632 famsl (feet above mean sea level). The maximum possible lake elevation is 667 famsl and the maximum depth at the normal lake level is 165 feet (USACE 2010c). Lake levels have varied between 619.9 famsl and 652.6 famsl over the period from 1979 through 2010 (USACE 2010b, 2010c). Figure 1 shows Lake Tenkiller and the surrounding area.

Methods

A flowchart representing both hydrologic and economic characteristics of the model is presented in Figure 2. As shown in this schematic representation, total stochastic inflow of water was distributed among marketed (urban and rural water supply and hydropower uses) and non-marketed[1] (recreation) uses. The economic benefits derived from recreational uses was obtained by multiplying visitor days (visitors times the average number of days they spend at the lake) by the value of a visitor day. Economic benefits of hydropower production were obtained by multiplying the amount of hydropower produced based on the water released for this purpose and the head of the reservoir, i.e. average lake level above the turbine by price of electricity. Economic benefits arising from urban and rural water supply uses depend on consumer surplus plus producer surplus derived from monthly/weekly water demand (the area below the demand curve and above the supply curve).

Mathematical Model

A non-linear programming model developed for the Broken Bow reservoir in Oklahoma (Mckenzie 2003) was modified to allocate Lake Tenkiller water among competing uses given stochastic monthly or weekly inflows, on-peak and off-peak water demand for hydroelectricity, urban and rural water supply, and recreational uses for the year 2010. The Frontline Risk Solver (Fylstra 2010) was used to solve the model. Total net expected economic benefits were

[1] In this study non-market valuation is limited to only "use values". A more extensive study could include "non-use values such as existence value, bequest values and option values. Thus, restricting the study to use values suggest more conservative results.

maximized over a year period by controlling monthly/weekly releases for hydroelectric power generation, and urban and rural water supply uses. The limited capacity of the Risk Solver limited problem size. So stochastic inflows were modeled monthly except during June, July, and August where they were modeled on a weekly basis. A mass balance equation was used to determine the monthly/weekly level and volume of water in the lake given the inflows and outflows. The model was specified as:

Maximize:

$$E(TB) = \sum_{t=1}^{T} (E(HB_t) + E(RB_t) + URB_t), \tag{1}$$

where $E(TB)$ = Expected total economic benefits for the year 2010, $E(HB_t)$ = Expected hydroelectric power generation benefits in month/week t, $E(RB_t)$ = Expected recreational benefits in month/week t, and URB_t = Urban and rural water supply benefits in month/week t and T is the combinations of month and week for the year 2010.

According to USACE (2010C), top of the flood pool for Lake Tenkiller is 667 famsl. Flood risk management in the model is implicitly considered by always maintaining the lake level below 640[2] famsl. An upper bound of 640 famsl was imposed on the lake level to maintain flood control capacity. The reservoir mass balance equation (Mckenzie 2003) determines the ending monthly/weekly reservoir volume from the beginning volume plus expected inflows (including precipitation), and less outflows (hydropower generation releases and other releases), and evaporation:

$$V_{t+1} = V_t + E(I_t) - O_t - E_t \tag{2}$$

$V_{min} \le V_t \le V_{max}$, $O_{min} \le O_t \le O_{max}$, $V_t, I_t, O_t \ge 0$,

[2] 8 to 10 feet rise of lake level above the normal pool of 632 famsl results in the picnic area under water. Therefore, in this study conservatively flood pool level was considered at 640 famsl.

where V_{t+1} = Volume of water in the reservoir in month/week t+1, V_t = Volume of water in the reservoir in month/week t, $E(I_t)$ = Expected inflow of water to the reservoir in month/week t, O_t = Outflows of water from the reservoir in month/week t, and E_t = Evaporation of water from the reservoir in month/week t, V_{min} = Minimum volume of water in the reservoir, V_{max} = Maximum volume of water in the reservoir, O_{min} = average minimum historical outflows of water from the reservoir, and O_{min} = average maximum historical outflows of water from the reservoir. The bounds on the downstream releases are to protect the trout fishery of lower Illinois river, which is around ten miles below the dam.

Monthly inflows were tested as to whether or not they could be modeled lognormal distributions (Wang et al. 2005). The acceptability of using the lognormal function to represent reservoir inflows over the October 1979 - May 2010 (USACE 2010a, 2010b) period was confirmed with the Kolmogorov-Smirnov goodness of fit test (Phillips 1972). Simulated average monthly/weekly inflows and their standard deviations were compared against the historical monthly/weekly inflows mean and standard deviations, as shown in Table 1.

Hydroelectric Power Generation Benefits

The economic benefits arising from hydroelectric power generation was obtained by multiplying the amount of electricity produced in each period by the price of electricity (USEIA 2010) for that particular period. Southwestern Power Administration (SWPA) delivered the total amount of hydroelectricity generated by Lake Tenkiller to the not-for-profit Oklahoma Municipal Electric Systems at a rate of 2.8 cents per kilowatt-hour (SWPA 2007). However, in this study, both average wholesale and retail monthly electricity prices were used (USEIA 2010). Table 2, shows peak and normal average wholesale and retail hydroelectric price used in this study. Whether incremental amounts of electricity should be valued at the wholesale or retail price depends on the marginal costs of distribution. If the marginal distribution cost is very low the retail price serves as an upper bound. If the marginal distribution cost is very high, the wholesale price serves as the lower bound for electricity values. It was assumed that all electricity generated between 3 pm through 7 pm during the summer months of June, July and August was sold at a peak rate that was $0.02 per kilowatt hour (OEC 2010) above the wholesale or retail market price for that particular period.

The OLS regression method was used to estimate the hydroelectric power generation equation (ReVelle 1999) based on the daily water releases, lake level (effective head) data (USACE 2010a, 2010b) and the amount of electricity produced over the period of January 1995 through December 2000 (USACE 2000). The estimated equation was as follows:

$$MW_t = \underset{(1152)}{0.232457}\, Head_t \times Qrel_t \qquad R^2 = 0.99, \tag{3}$$

where MW_t = electricity (megawatt hour) generated in period t, $Qrel_t$ = water (acre feet) released in period t, and $Head_t$, = head (feet) in period t. ("t" value in parenthesis).

Urban and Rural Water Supply Benefits

The water demand model required monthly consumption values for a mixture of municipalities and rural water districts. Annual water consumption values are readily available for municipalities (OLM 2008). Attempts to survey rural water districts in the area were unsuccessful. However, the authors obtained monthly, 2001 through 2007, water treatment plant operation reports from the Oklahoma Department of Environmental Quality (ODEQ 2008). These reports were from Muskogee, Muldrow, Sallisaw, Gore, Eufaula, and Roland. The cities selected were those where water consumption by the population served by each city could be separated from the service area of rural water districts and matched with the quantity of water reverenced in the water treatment reports. Then a monthly per-capita water demand model

(Borland, 1998) was estimated using SAS PROC MIXED (Littell et al. 2008). The city and annual variables were considered to be random.

The estimated monthly per capita water demand (gallons) equation based on the mean population was as follows:

$$Q_{m,c} = \underset{(7.82)}{5.23}\ Jan + \underset{(6.71)}{4.49}\ Feb + \underset{(7.09)}{4.74}\ Mar + \underset{(6.76)}{4.52}\ Apr + \underset{(7.58)}{5.07}\ May + \underset{(8.1)}{5.41}\ Jun + \underset{(10.08)}{6.74}\ Jul$$

$$+ \underset{(10.12)}{6.76}\ Aug + \underset{(8.78)}{5.86}\ Sep + \underset{(8.34)}{5.58}\ Oct + \underset{(7.41)}{4.96}\ Nov + \underset{(7.41)}{4.95}\ Dec + \underset{(4.15)}{1.24}\ Pop_c \qquad \text{Chi}^2 = 372.30, \tag{4}$$

where $Q_{m,c}$ = per capita water demand (in thousand gallons) in city c in a particular month m; *Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec* = dummy variables (January through December), which took 1 for a particular month and 0 for other months; and Pop_c = relative population (*Pop/(mean Pop)*) of a particular city c. ("t" value in parenthesis).

The price of water (P_m) was rounded to $3 per thousand gallons which was equal to pumping costs estimated from EPANET above, plus administrative costs (OML 2008). The summer and winter price elasticities (ρ_m) were considered as -0.25 and -0.04 respectively obtained from IWR Main (Davis et al. 1987). Monthly proposed water demand[3] by the 27 water districts, including urban areas of Tahlequah, Gore, Vian, Sequoyah, and Muskogee (USACE 2001) and in counties surrounding Lake Tenkiller was derived by multiplying the estimated monthly per capita water demand by the total population served under these water districts shown in Figure 8. During the summer months of June through September, the urban and rural water demand is at its peak mainly because of watering of the lawns. The combined demand was approximately five million

[3] The proposed water demand by the Lake Tenkiller and its surrounding area was much less than the supply reallocated using 1958 WSA (Water Supply Act) authority.

gallons per day. The consumer surplus[4] derived from urban and rural water supply was calculated by integrating the price flexibility form of the demand function.

$$CS_t = \int_0^{Q_t} (\alpha_t + \delta_t Q_t) dQ_t, \tag{5}$$

where CS_t = consumer surplus in month/week t, $\alpha_t = (P_t - \delta_t Q_t)$ intercept of the inverse demand function, and $\delta_t = (P_t / Q_t) \times (1/\rho_t)$ slope of the inverse demand function.

The total welfare derived from urban and rural water supplies was obtained by subtracting the supply (pumping) cost from the consumer surplus.

Lake Recreation Benefits

In this study, the assumption that the number of monthly lake visitor was dependent on deviations of the lake from its normal level of 632 famsl was tested using monthly data from 1955 through 2010. Monthly visitor data from the period of 1975 through 2010 September were obtained from USACE (2010a). Secondary data over the period of 1955 through 1974 published by Badger and Harper (1975) were also used for this study. A quadratic relationship between the number of visitor and deviations in the lake level above and below its normal level was estimated by regressing the monthly visitors against the deviated lake level for the same periods using maximum likelihood estimation. The estimated regression equation used in this study was:

$$V_{m,y} = 86302 + \underset{(5.38)}{105821}\, Apr + \underset{(13.12)}{260192}\, May + \underset{(8.88)}{288535}\, Jun + \underset{(11)}{335015}\, Jul + \underset{(7.22)}{218473}\, Aug$$

$$+ \underset{(6.67)}{130746}\, Sep + \underset{(1.11)}{718}\, ALkLv + \underset{(2.07)}{13001}\, LvJun + \underset{(1.91)}{1401}\, Tsumr_y - \underset{(-1.22)}{236}\, Lv_{Jn}^2$$

$$- \underset{(-2.99)}{1186}\, Lv_{Jly}^2 - \underset{(-1.22)}{236}\, Lv_{Aug}^2 \tag{6}$$

$$2logLR = 17146.3,$$

where V_m = number of visitor in a month; *Apr, May, Jun, Jul, Aug* and *Sep* = 0-1 dummy

[4] Consumer surplus is the area under the demand curve.

variables which were 1 in the indicated month and zero otherwise; $Tsumr_y$ = time trend for months June, July, and August (the number of visitor in other months did not vary significantly with time)for the year *y*; *ALkLv* = difference between the actual and normal lake level (632 famsl) when the lake level is below the normal level else zero; *LvJun* = discrete variable to test if visits to the lake in June were more sensitive to lake levels than in other months; Lv_{Jn}^2, Lv_{Jly}^2, Lv_{Aug}^2 = squares of the difference between the actual and normal lake level (632 famsl) for the months of June, July, and August respectively ("t" value in parenthesis). The only significant trend in the number of visitor was during June, July, and August. The time trend in summer visitors 1401, is measured by the variable $Tsumr_y$. The effect of the *LvJun* variable when combined with the *ALkLv* (average lake level) and the quadratic terms is to make the June visitors more sensitive with respect to lake levels above and below the normal level as shown in panel a of Figure 4.

The number of monthly visitors was found to increase with lake levels until it reached the normal level of 632 famsl in June, July, and August, mainly because the visitors are sensitive to the lake level for Lake Tenkiller, which is famous for skiing, hiking and scuba diving. As implied by the quadratic lake level terms in equation 6, the number of visitors began to decline when the lake level increased above 632 famsl during the months of June, July and August. Any lake level below the normal pool will reduce the depth for scuba divers while any level above the normal pool will results in the flash flood and also increase the navigational hazard. Figure 4 shows the effect of the lake level on visitors in July was stronger than in June or August. It should be noted that both the predicted number of visitors at each lake level and the actual number of visitors have been adjusted to 2010 values. The actual number of visitor has been adjusted upward by an amount equal (2010 –Year reported)*1401, where 1,401 in the summer time trend coefficient mentioned earlier. Finally, monthly visitors were then converted into visitor days by multiplying the total monthly visitors by the average number of days each visitor spend at the lake. However, for Lake Tenkiller on average each visitor spends a single day at the lake (USACE 2010a).

According to economic guidance memorandum (Carlson, 2009) based on the unit day value method, the value of a visitor day ranges between $3.54 and $10.63 for general recreation. However, Gajanan et al. (1998) found that the economic value of lake recreation derived from motor boating and waterskiing ranges between $9.85 and $45.61, and it varies across different ecoregions in United States. Boyer et al. (2008) estimated the recreational value of Lake Tenkiller as part of a larger random utility travel cost model for all lakes in Oklahoma and found the value of a visitor day to Lake Tenkiller was around $191 in 2008, the highest value for any Oklahoma lake. Badger and Harper (1975) using travel cost method found that the value of a visitor day at Lake Tenkiller was $4.67, which is equivalent to around $24 in 2010 prices.

Two values for a visitor day were used in this study. The low value was $10 per visitor day as per Carlson (2009). The upper value was $50 per day (about one-fourth the value estimated by Boyer et al. (2008)).

An additional study by Roberts et al. (2008) had shown that the willingness to pay for a visitor day at Lake Tenkiller declined by $0.82 for each foot the lake was below the normal level. Figure 5(a) and 5(b) show how the value of a visitor day was decreased in the model from $50 and $10 (when the lake level was 632 famsl or more), to $43 and $3 per day (when the lake level was 624 famsl or less). Total recreational benefits were calculated by multiplying the visitor days (obtained from the estimated number of visitor) by the value of a visitor day at the indicated lake level. Table 3, shows the recreational benefits derived from different lake levels for the month of August 2010. This study is also unique as both the number of visitor and the value of a visitor day vary with the level of the reservoir.

Results

Effect of Including Recreation as an Optimizing Variable

Effect of explicitly including or not including recreation benefits in the lake management optimization function (Objective 2) and its impact on the net economic benefits were measured by comparing two scenarios. In the first scenario, economic benefits were maximized with respect to releases for hydropower generation, and public water supply uses only. Recreational benefits were calculated post optimization from resulting lake levels. In the second scenario, net economic benefits were maximized with respect to recreation, hydropower generation, and public water supply. Hydropower was assumed to be sold at the peak retail electricity prices shown in Table 2 and the base visitor day was assumed to be worth \$50 in both scenarios. Table 4 shows that net annual economic benefits were \$214.09 million when optimized with respect to hydropower and public water supply use, and recreation benefits were determined after the optimization. When recreational benefits were directly considered in the economic optimization model (scenario 2), the net annual economic benefits were \$217.77 million. The estimated annual gain of \$3.68 million from the lake resource was approximately 1.72 percent. Recreation benefits were increased by \$3.8 million or three percent while the value of hydropower generation declined by approximately \$0.09 million, shown in Figure 9. The ratio of the increase in recreation benefits per dollar of hydropower loss was 42 to 1. Public water supply uses remained essentially unchanged between scenarios 1 and 2, because in the case of Lake Tenkiller, the proposed demand for domestic water use is much more inelastic than the demand for recreational and hydropower generation use.

When focusing on hydropower in scenario 1, the optimal strategy was to raise lake levels from the normal 632 to 640 feet above mean sea level (Figure 6), to increase head and power generation during the summer months when both hydropower price and demand were at their peak. However, when recreation was considered (scenario 2), in the objective function, the optimal strategy was to maintain levels slightly above the normal pool of 632 famsl from May through mid August and maximize visitor numbers during the summer. It should be noted that historical levels are very close to scenario 2 levels on May and June but are lower from July through October. This indicates the current management strategy is not one of strictly maximizing hydropower production.

The model was further used to calculate the net economic benefits given the historical average lake levels shown in Figure 6. The purpose was to estimate the net total economic benefits that would be obtained in the year 2010 if the lake levels were constrained to average historical lake levels of years 1979-2010, with estimated 2010 visitor numbers and public water demands. It was found that for year 2010, total annual economic benefits derived from the average historical lake levels would be around $215.03 million, which was around $2.74 million lower than in scenario 2, with recreation benefits in the objective function. That is, the historical (1979-2010) levels were near optimal shown in Figure 6 except for July through October. One of the reasons for these levels is the early draw down to meet the peak electricity demand. It is also worth noting that optimal lake levels obtained from the stochastic optimization model are higher and much closer to the historical levels than the levels obtained under deterministic optimization shown in Figure 7. This is because with lognormal inflows, the mean inflow is greater than the more likely median inflow. Releasing more water under the expectation of receiving a mean inflow would increase the number of years when the actual level was below normal. There was around $219.87 million total economic benefits derived under deterministic condition which was around $2.10 million higher than the stochastic solution. The comparison of the total economic benefits among these three different situations (stochastic, deterministic and historical) was shown in Figure 10. The optimal stochastic lake levels from June through mid-July are almost identical to the average historical levels.

Sensitivity of Optimal Lake Levels to Recreation Values and Electricity Prices

Further the model was solved with three different combinations of values for a visitor day and peak electricity prices. These combinations were: (i) $50 value of a visitor day – peak retail hydroelectricity prices, (ii) $10 value of a visitor day – peak retail hydroelectricity prices and (iii) $10 value of a visitor day – peak wholesale hydroelectricity prices. These are scenarios 2, 3, and 4 respectively. Optimal number of visitor and the amount of hydropower produced under 2, 3, and 4 are shown in Table 4. The results show there is very little different between the three solutions. That is even when recreation is valued at $10 per day and electricity is prices at peak retail rates, there was a little increase in hydropower production when the electric prices increased from wholesale to retail and the value of a visitor day was decreased from $50 to $10. The optimal August lake level remains above the average historical August level for all three scenarios shown in Figure 8. However, maintaining a normal lake level of around 632 famsl during the summer months of June, July, and August for Lake Tenkiller was beneficial to maximize both the recreational and hydropower generation benefits since any lake level above and below the normal lake level of 632 famsl would definitely reduce the number of visitor for those months. By contrast, in the model where hydroelectric power generation benefits were the main concern of the management (lake recreational benefits were not included in the objective function), then it would be beneficial to increase the lake level (head) above the turbine and release water during the summer months when the electricity price was at its peak. The results show that during June, July, and August, when the number of visitor was at its peak, the lake level should be maintained two to three feet above the normal lake level of 632 famsl and some of the releases for hydroelectric power generation should be shifted to the spring and fall periods. The Scenario 2 results predict that there were around 241,018 more visitors compared to scenario 1, if the lake level were maintained slightly above the normal level through mid August, as shown in Figure 11. The main increase of 188,118 visitors was predicted to occur in July.

In Table 6, the August visitor days were predicted to reach a maximum of 381,830 visitor days at the normal lake level of 632 famsl (Table 3). So, as the level is lowered from 637 to 636 famsl, additional 13.72 thousand acre feet are released and $88.34 thousand dollars of electricity are generated. As the lake level is lowered toward normal (from 637 to 636 feet), the number of visitor increases, adding and $21.24 thousand in recreational benefits for a total of $109.58 thousand. The total value of economic benefits derived from the lake resource continues to increase though by smaller amounts until the lake level has reached 632 famsl. At this level, for the month of August, there is the highest number of visitor days (Table 3). The increase in the aggregate lake value is the change in the value of electricity produced plus the gain in the recreational value (number of visitor days multiplied by $10 per day). However, as the level is lowered below 632 the value of the visitor day declines as shown in Figure 5b. While the decline from $10 per day at 632 famsl to $9.18 famsl seems small, the value of total recreation benefits at 631 feet is obtained by multiplying 380,886 visitor days by $9.18 (Table 3). Thus, the value of recreation benefits declines by $321,858 for the one foot decline between 632 and 631 famsl which are three times greater than the value of additional electricity generated. Thus, for Lake Tenkiller, the finding is that total economic benefits derived from the lake resource are maximized by maintaining the lake level two to three feet above normal in June, July and declining to the normal lake level of 632 famsl by mid August. That is inclusion of recreation values as a variable in the optimization model indicates a higher than the historical level should be maintained during July and August to increase recreational benefits.

Results obtained from this optimization model satisfy the equi-marginal principle while allocating Lake Tenkiller water among (a) recreational use, (b) hydroelectric power generation use, and (c) urban and rural water supply use. That is, it is not possible to take one additional acre foot of water from hydropower and transfer it to urban and rural water use or to recreational use and increase the total economic benefits arising from Lake Tenkiller water uses. The marginal value or shadow price of water in each alternative use must be equal when measured at the lake. Table 7, column (2) shows the marginal cost of treatment and delivering an acre foot of water. The marginal price of water delivered for urban and rural water supply use is higher by the amount of treatment and delivery cost of water supplying to the surrounding area of Lake Tenkiller ($257.64). This result occurs because the users are usually charged only the cost of treatment and delivery, but not the cost of holding water for alternative uses. Thus the consumer receives 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 is the opportunity cost (cost that the lake managers are incurring by not using one acre foot of water for other purposes) of water at the lake shown in column 7 of Table 7.

Discussion

The results are interesting since neither urban and rural water supply use nor recreational use was considered the primary uses when the dam was constructed (USACE 2009). The results show the value of electricity that could be generated by releasing more water and lowering the lake level below the normal level of 632 famsl in the summer period is more than offset by reduced recreation benefits. This result differs from the results obtained by Ward and Lynch (1996) for reservoirs in New Mexico. This difference is in part because the number of monthly summer visitors to Lake Tenkiller varies from 400 to over 500 thousand and there is a change in willingness to pay due to the change in the lake level, in part, because the head above the turbines is lower for Lake Tenkiller than for the Rio Chama Basin of New Mexico. It was also found that in the absence of stochastic inflows the model overestimates total economic benefits. The optimal management plan is also influenced by the head of the reservoir. If the reservoir had higher elevation (head) over the turbine, then the value of hydroelectric power generation would increase relative to the lake recreational benefits. The results indicate that the average lake level maintained over the years 1979-2010 would provide near optimal 2010 benefits except for mid July through October. Therefore, for Lake Tenkiller it is suggested that the releases for hydropower generation should be delayed till mid August

The economic optimization model developed and used in this study is able to test several different management policies. This type of model could be used to identify the economic impacts of different types of allocation patterns by controlling the releases. The model's ability to allocate water among multiple uses over the different time period under stochastic inflows and to change the optimal usage pattern under different conditions makes it a unique and valuable tool for the governmental policy analysis. This model is also helpful in any further cost benefit analysis since it provides the shadow price (opportunity cost) of water at the lake. The modeling approach used in this study may be useful for the policy makers to compare different management scenarios and compare the impact of each strategy on the net economic benefits.

This can help water managers and policy makers to test different water management policies and implement them while managing a reservoir.

Acknowledgements

The authors were grateful to Oklahoma Water Resources Research Institute (OWRRI), Oklahoma Water Resources Board (OWRB) and U.S. Geological Survey (USGS) for financially supporting this research work.

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Table 1.-Simulated average monthly inflows and standard deviation compared with historical average inflows and standard deviation (1979-2010).

Historical	Inflow (Ac-ft)		Simulated	Inflow (Ac-ft)
Month	Average	Standard Deviation	Average	Standard Deviation
Jan	109,190	103,977	109,034	101,854
Feb	109,935	79,689	109,839	78,741
Mar	164,909	116,659	164,752	115,131
Apr	165,468	122,134	165,377	121,443
May	150,209	124,650	150,330	125,042
Jun week 1	26,041	20,695	26,021	20,510
Jun week 2	26,495	28,011	26,442	27,310
Jun week 3	33,492	55,420	33,534	54,739
Jun week 4	23,753	43,666	23,627	40,694
Jul week 1	18,046	26,716	17,966	25,274
Jul week 2	12,774	16,508	12,756	16,033
Jul week 3	8,484	6,621	8,494	6,748
Jul week 4	9,127	10,060	9,117	9,854
Aug week 1	7,366	10,104	7,521	12,792
Aug week 2	8,855	9,634	8,835	9,374
Aug week 3	6,753	5,829	6,760	5,876
Aug week 4	4,927	3,052	4,924	3,031
Sepr	42,178	50,478	42,098	49,152
Oct	67,228	110,225	67,620	114,918
Nov	92,538	95,267	92,449	94,092
Decr	116,470	117,299	116,310	115,115

Table 2.-Wholesale and wholesale peak and retail and retail peak electricity price per kilowatt-hour for the year 2010.

Month	Wholesale electricity price	Wholesale peak electricity price	Retail electricity price	Retail peak electricity price
Jan	$0.05	$0.05	$0.07	$0.07
Feb	$0.05	$0.05	$0.08	$0.08
Mar	$0.04	$0.04	$0.07	$0.07
Apr	$0.04	$0.04	$0.07	$0.07
May	$0.04	$0.04	$0.07	$0.07
Jun	$0.05	$0.07	$0.07	$0.07
Jul	$0.05	$0.07	$0.08	$0.10
Aug	$0.06	$0.08	$0.08	$0.10
Sep	$0.04	$0.04	$0.08	$0.10
Oct	$0.03	$0.03	$0.07	$0.07
Nov	$0.03	$0.03	$0.07	$0.07
Dec	$0.04	$0.04	$0.07	$0.07

Table 3.-Visitor days, value of a visitor day starting at $10 and recreational benefits for different lake levels for the month of August 2010.

Lake level	Visitor days	Value of a visitor day	Recreation benefits
638	373,334	10.00	3,733,340
637	375,930	10.00	3,759,300
636	378,054	10.00	3,780,540
635	379,706	10.00	3,797,060
634	380,886	10.00	3,808,860
633	381,594	10.00	3,815,940
632	381,830	10.00	3,818,300
631	380,876	9.18	3,496,442
630	379,450	8.36	3,172,202
629	377,552	7.54	2,846,742
628	375,182	6.72	2,521,223

Table 4.-Comparison of total economic benefits from Lake Tenkiller when recreational values were and were not included in the objective function for 2010.

Recreational values in objective function***			Recreational values not in objective. function***		
Recreation* benefits	$	126,392	Recreation* Benefits	$	122,593
Hydropower** benefits	$	6,890	Hydropower** benefits	$	6,977
Rural water supply (RWS)	$	84,518	Rural water supply (RWS)	$	84,518
Total benefits (with recreation in objective function)	$	218,099	Total benefits (without recreation in objective function)	$	206,969

*Recreation valued at $50 per visitor day when lake level is 632 feet and above; **Hydropower valued at the average monthly retail peak electricity price; ***values in thousand dollars

Table 5.-Sensitivity of the estimated number of monthly visitors and hydropower production to changes in the value of a visitor day from $50 per visitor day to $10 per visitor day when hydropower is valued at 2010 wholesale or retail peak electricity prices.

	Visitors			Hydropower-generation		
Scenario	2	3	4	2	3	4
Value of a visitor day	$50	$10	$10	$50	$10	$10
Monthly Electricity Price	Retail	Retail	Wholesale	Retail	Retail	Wholesale
Month		Number			MwH	
Jan	86,302	86,302	86,302	9,235	9,198	9,234
Feb	86,302	86,302	86,302	8,455	8,417	8,454
Mar	86,302	86,302	86,302	11,130	11,140	11,129
Apr	191,597	191,597	191,597	8,917	8,937	8,917
May	345,555	345,555	345,555	13,716	13,717	13,712
Jun week 1	104,851	104,839	104,840	3,144	3,165	3,143
Jun week 2	104,779	104,768	104,772	1,813	1,784	1,812
Jun week 3	105,595	105,583	105,591	2,797	2,818	2,794
Jun week 4	105,568	105,561	105,567	3,391	3,356	3,387
Jul week 1	123,920	123,932	123,916	1,459	1,551	1,458
Jul week 2	124,237	124,237	124,237	2,098	2,119	2,096
Jul week 3	124,180	124,175	124,181	614	618	613
Jul week 4	123,982	123,972	123,981	419	325	419
Aug week 1	92,913	92,910	92,913	385	386	385
Aug week 2	92,827	92,822	92,827	582	584	581
Aug week 3	93,009	93,008	93,009	127	116	127
Aug week 4	92,420	92,430	92,420	731	581	731
Sep	215,739	215,755	215,766	2,520	2,524	2,518
Oct	86,219	86,256	86,244	2,485	2,557	2,483
Nov	86,302	86,302	86,302	9,301	9,656	9,293
Dec	86,302	86,302	86,302	9,494	9,520	9,485
Total	2,558,899	2,558,909	2,558,926	92,812	93,068	92,769

Table 6.-Effect of releasing water to create a one foot decline in the lake level from 637 to 630 feet above sea level on hydropower values and recreational benefits for August of 2010.

Level	Volume of release (Ac-Ft)	Changes in hydro-electric value*	Change in number of visits	Changes in Recreation benefits**	Total change in net economic benefits
637-636	13,722	$88,335.03	2,124	21,240	$109,575
636-635	13,524	$86,417.26	1,652	16,520	$102,937
635-634	13,335	$84,571.25	1,180	11,800	$96,371
634-633	13,153	$82,792.14	708	7,080	$89,872
633-632	12,979	$81,075.45	236	2,360	$83,435
632-631	12,811	$79,417.07	-954	-321,858	-$242,441
631-630	12,650	$77,813.36	-1,426	-324,240	-$246,426

*electricity is valued at $0.07 per kilowatt hour; ** value of a visitor day at $10

Table 7.-Actual delivery cost of water, acre feet of water released for hydropower production, megawatt-hours (MwH) of hydropower produced, hydroelectric power generation benefits, shadow price for hydropower production, and the per unit price of water at the Lake Tenkiller for the year 2010 obtained from the optimization model when recreation values were included in the objective function.

Month	Actual cost of 1 acre foot of water	Water releases for hydro-power (acre feet)	Hydro-power production with recreation (MwH)	Hydro-power production benefits	Shadow price for per 1000 KwH of hydro-power production[a]	Price of 1 acre foot of water at the lake[b]
Jan	$263.27	114,721	9,234	$646,358	$70.00	$5.63
Feb	$263.82	104,928	8,454	$648,387	$76.70	$6.18
Mar	$263.15	136,255	11,129	$751,214	$67.50	$5.51
Apr	$263.48	106,039	8,917	$618,847	$69.40	$5.84
May	$263.44	165,000	13,712	$957,066	$69.80	$5.80
Jun week 1	$263.68	38,119	3,143	$230,298	$73.27	$6.04
Jun week 2	$263.69	21,946	1,812	$132,774	$73.27	$6.05
Jun week 3	$263.68	33,894	2,794	$204,716	$73.27	$6.04
Jun week 4	$263.61	41,566	3,387	$248,181	$73.27	$5.97
Jul week 1	$263.96	17,911	1,458	$113,218	$77.65	$6.32
Jul week 2	$263.90	25,990	2,096	$162,760	$77.65	$6.26
Jul week 3	$263.90	7,614	613	$47,631	$77.70	$6.26
Jul week 4	$263.90	5,193	419	$32,514	$77.60	$6.26
Aug week 1	$263.91	4,770	385	$29,911	$77.69	$6.27
Aug week 2	$263.91	7,213	581	$45,208	$77.81	$6.27
Aug week 3	$263.92	1,572	127	$9,868	$77.70	$6.28
Aug week 4	$263.89	9,085	731	$56,811	$77.72	$6.25
Sep	$263.82	31,224	2,518	$192,846	$76.59	$6.18
Oct	$263.75	30,241	2,483	$184,740	$74.40	$6.11
Nov	$263.61	114,890	9,293	$685,801	$73.80	$5.97
Dec	$263.40	117,551	9,485	$677,240	$71.40	$5.76

Note: Shadow Price: the extra amount of cost incurred in order to produce one additional unit of hydropower
[a] Column (6) is equal to Column (5) divided by Column (4), [b] Column (2) minus $257.64 (supply cost of per acre foot of water) is equal to column (7), [b] Column (7) is also equal to Column (5) divided by Column (3)

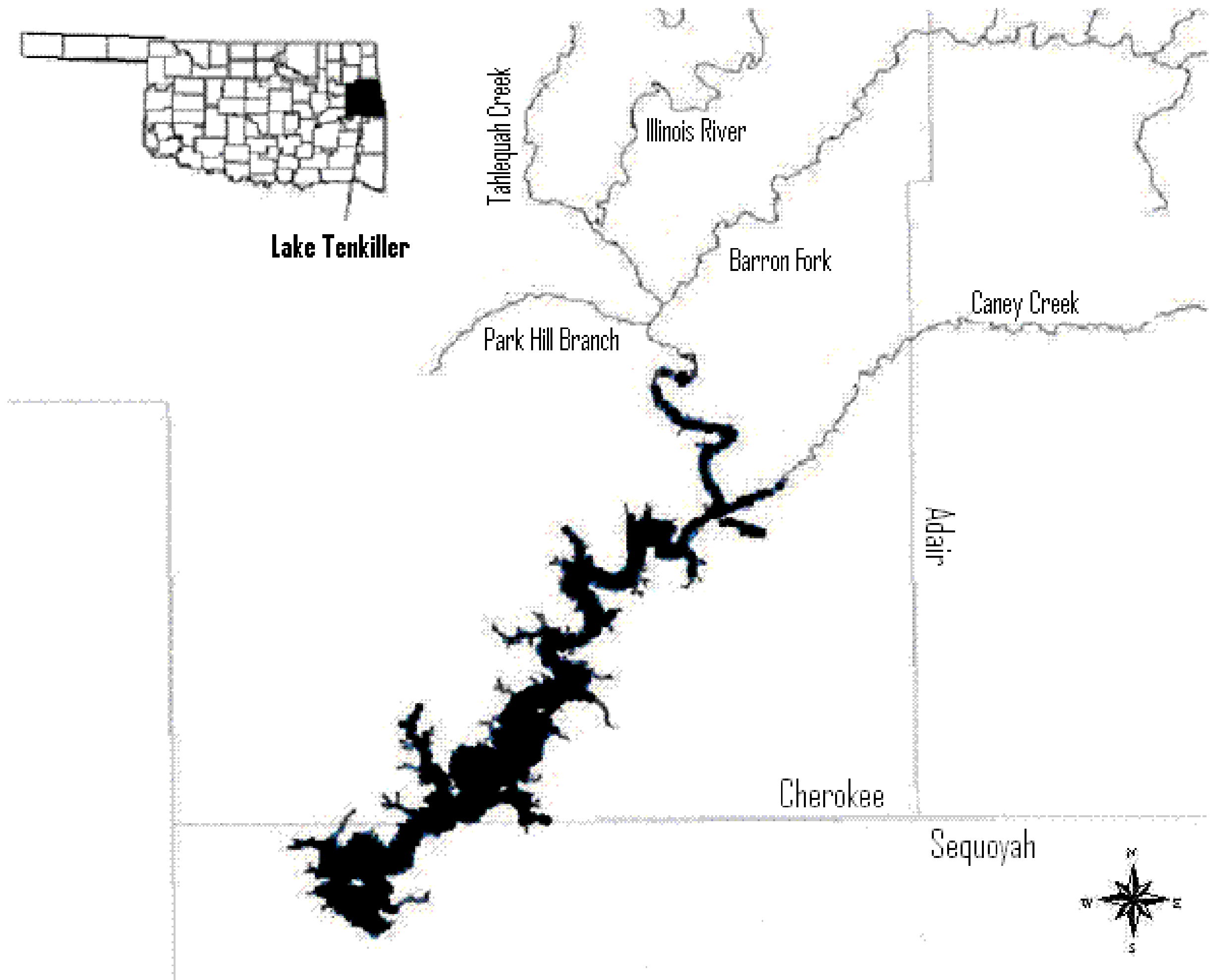

Figure 1.-Lake Tenkiller and its surrounding areas in Northeast Oklahoma.

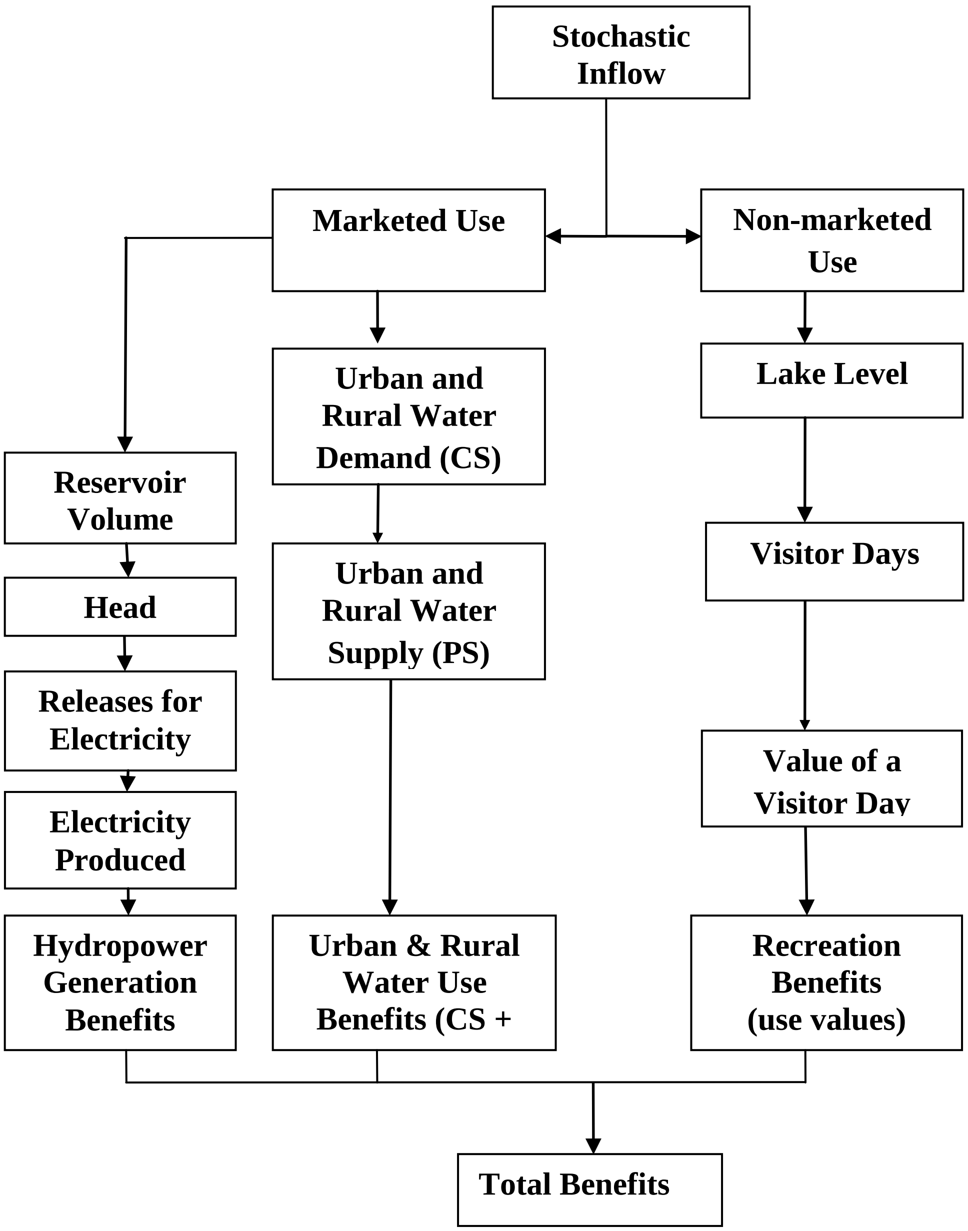

Figure 2.-Flowchart of the optimization model.

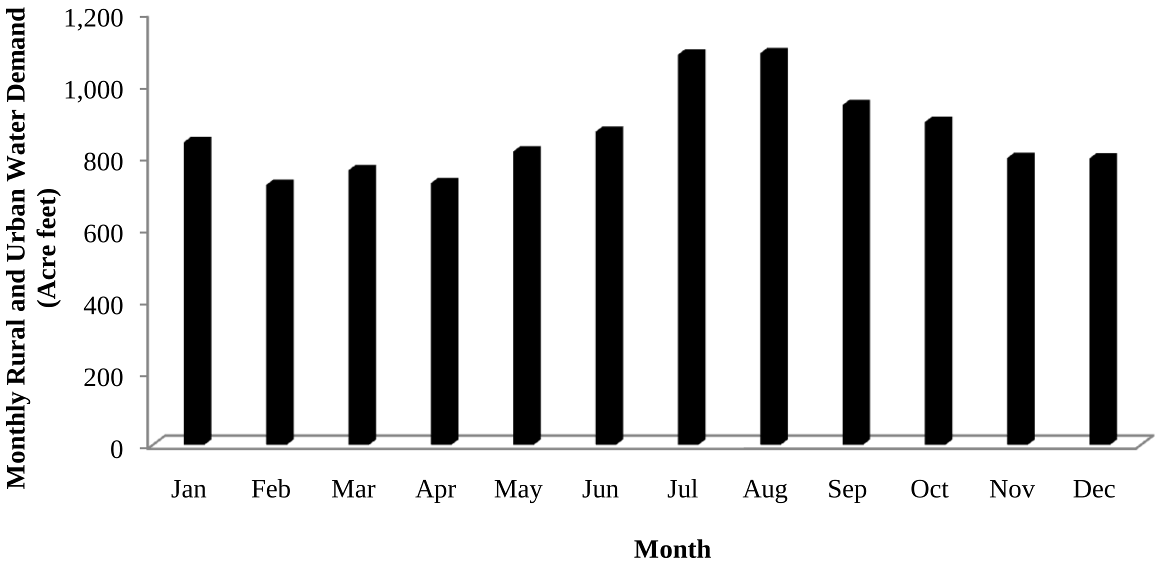

Figure 3.-Predicted urban and rural water demand (acre feet) for each month by the Lake Tenkiller and its surrounding area for the year 2010.

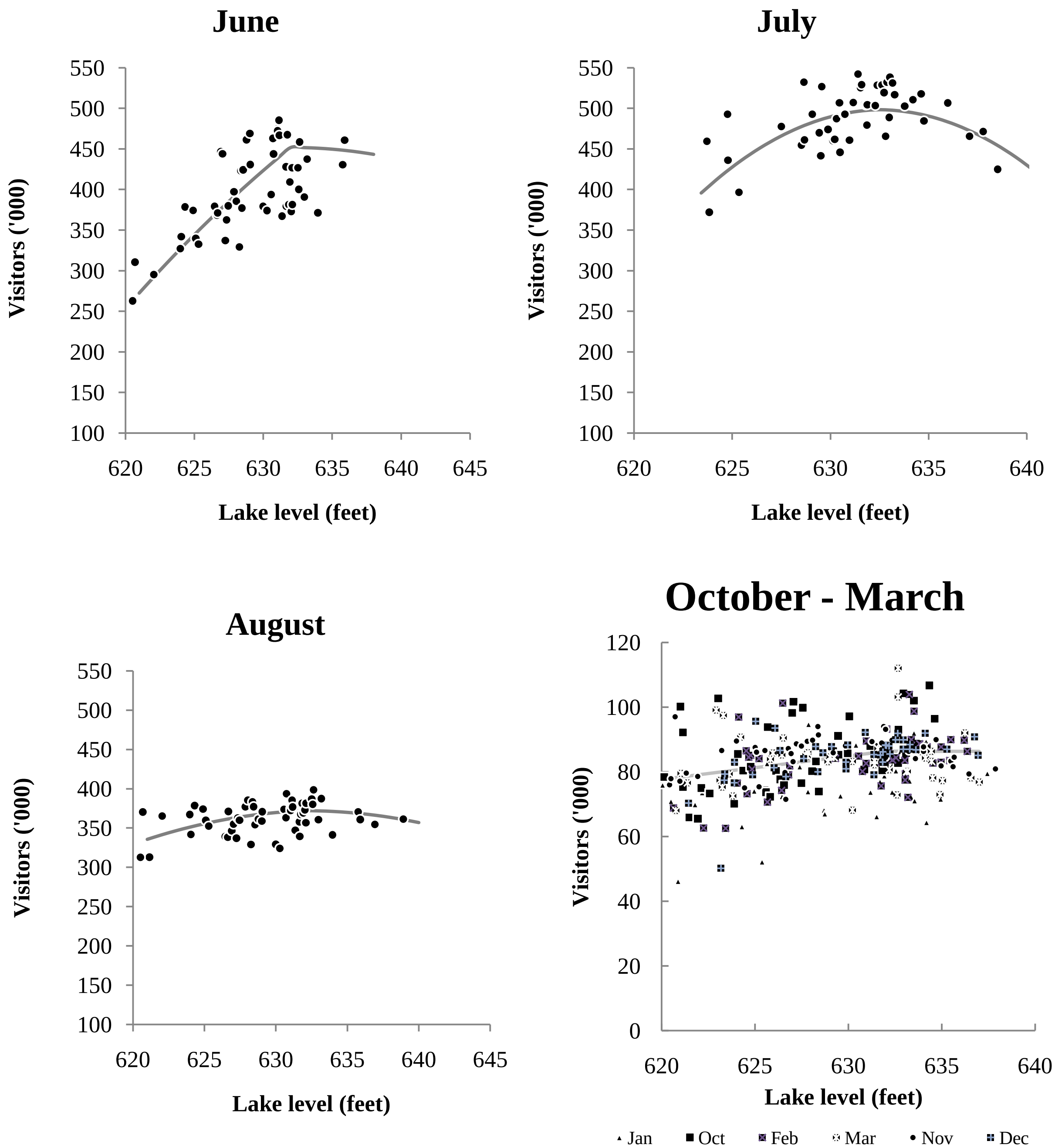

Figure 4.-Number of predicted versus actual adjusted to 2010 visitors by adding (2010-year reported)*1401 to the reported value visitors (in thousands) to Lake Tenkiller by lake level for the summer months of June, July, and August and predicted versus actual visitors for the months October through March in 2010.

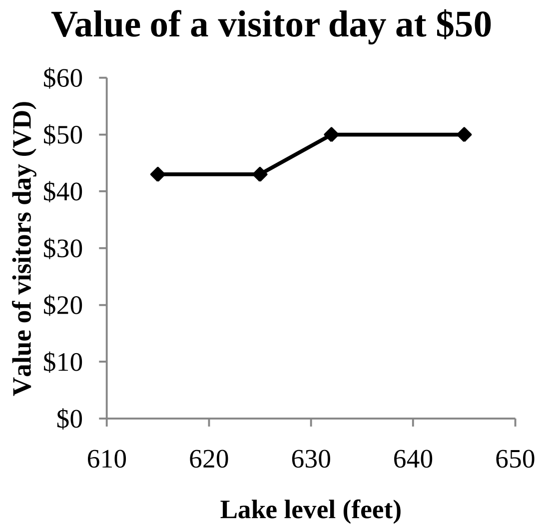

Figure 5a.-$50 per visitor day at Lake Tenkiller as a function of lake level

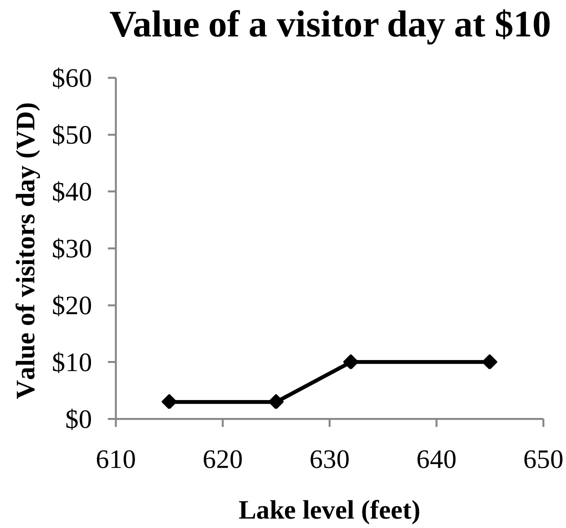

Figure 5b.-$10 per visitor day at Lake Tenkiller as a function of lake level.

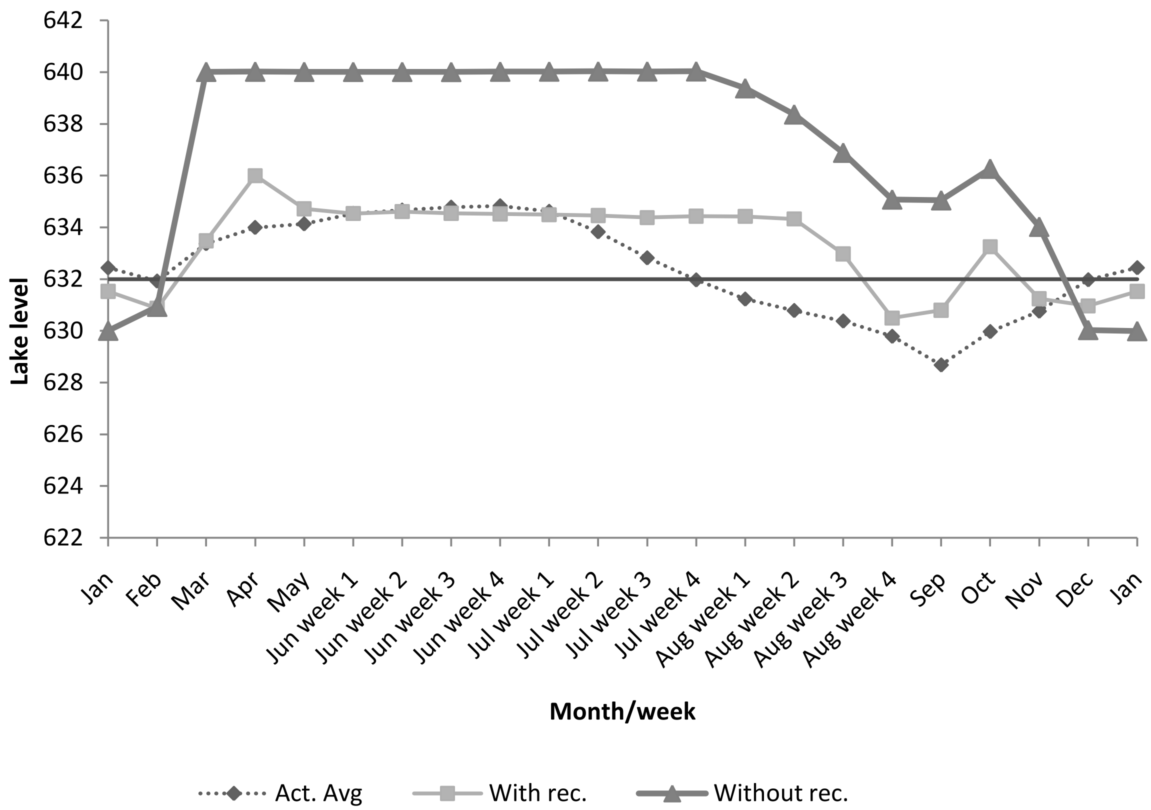

Figure 6.-Comparison between average historical monthly/weekly lake levels for Lake Tenkiller from 1979-2010 with the optimal lake levels for 2010 when recreational values were and were not included in the optimization model.

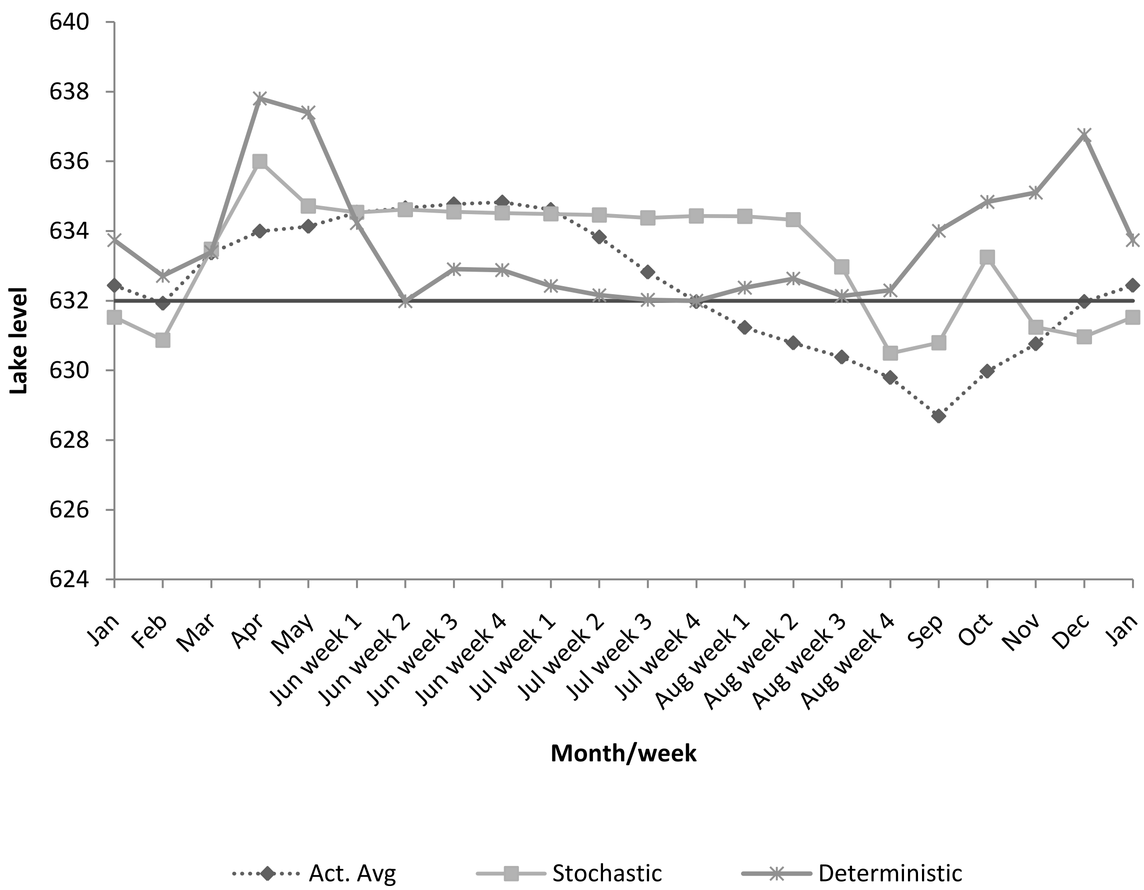

Figure 7.-Comparison between average historical monthly/weekly lake levels for Lake Tenkiller from 1979-2010 with the optimal stochastic lake levels for 2010 and with the optimal deterministic lake levels for 2010 (recreational values in the objective function).

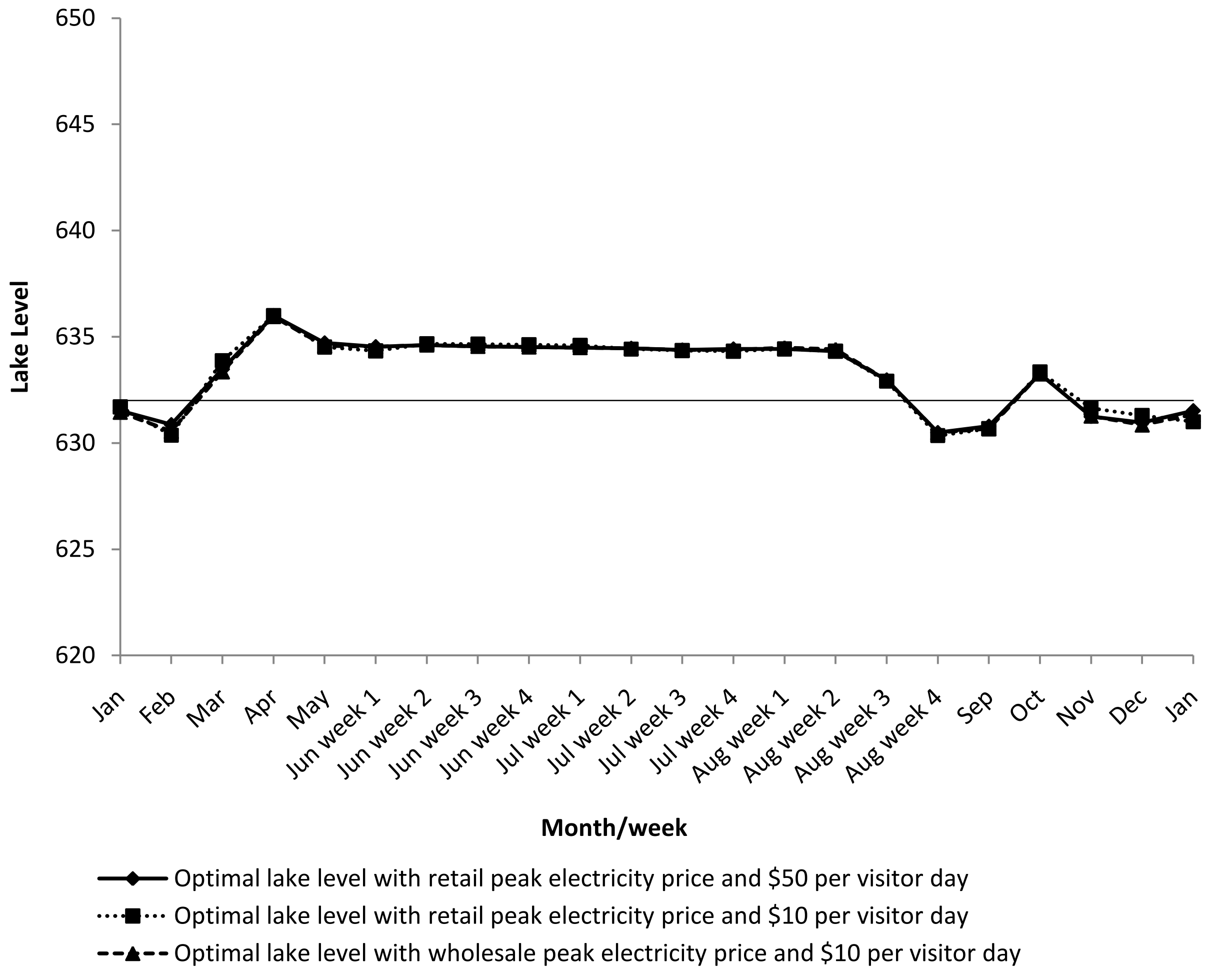

Figure 8.-Optimal lake level with recreational values included in the model for the year 2010 when (i) value of a visitor day is $50 and retail peak price of hydropower; (ii) value of a visitor day is $10 and retail peak price of hydropower; and (iii) value of a visitor day is $10 and wholesale peak price of electricity.

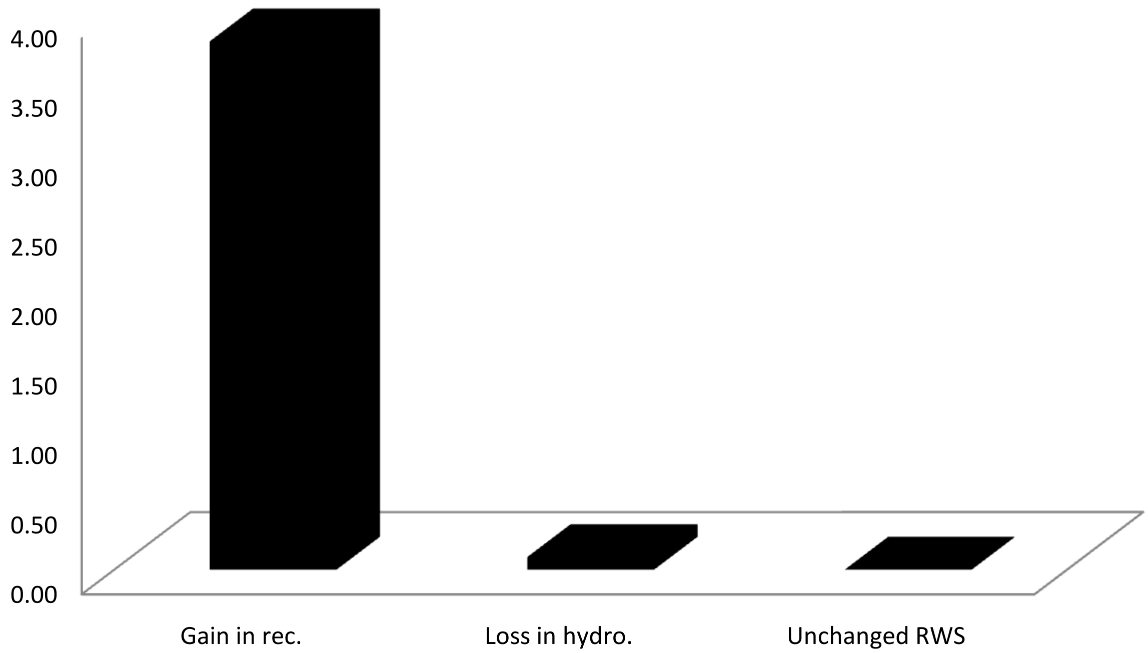

Figure 9.-Tradeoff between the loss in hydroelectric power generation values versus gain in lake recreational values when recreational values were included in the objective function for year 2010.

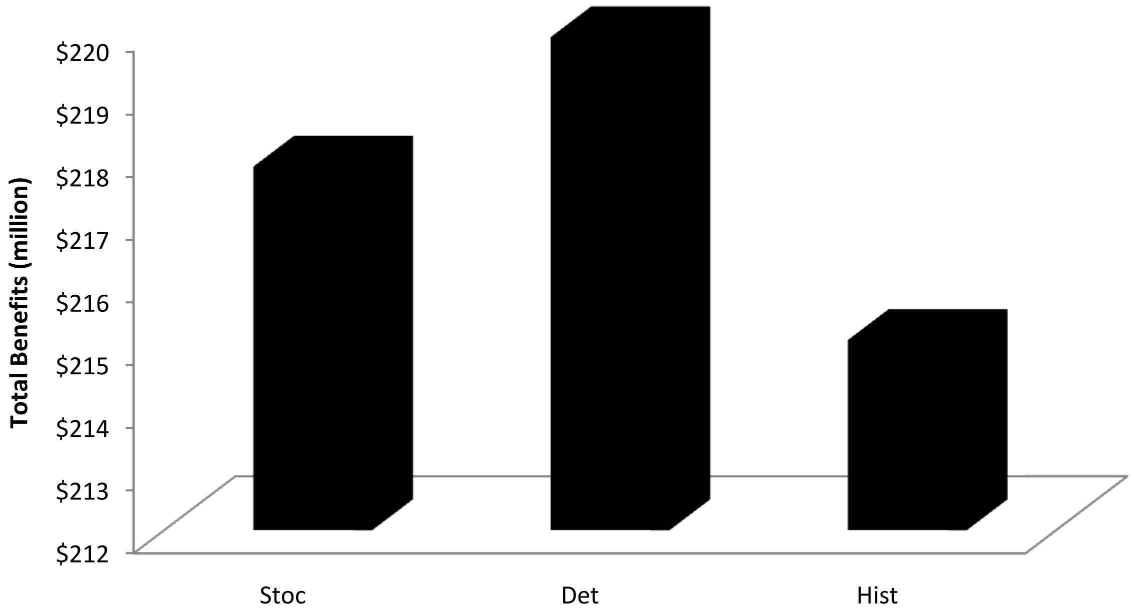

Figure 10.-Comparison between the total economic benefits derived for the year 2010 under three different situations: Stochastic, deterministic and average historical lake levels.

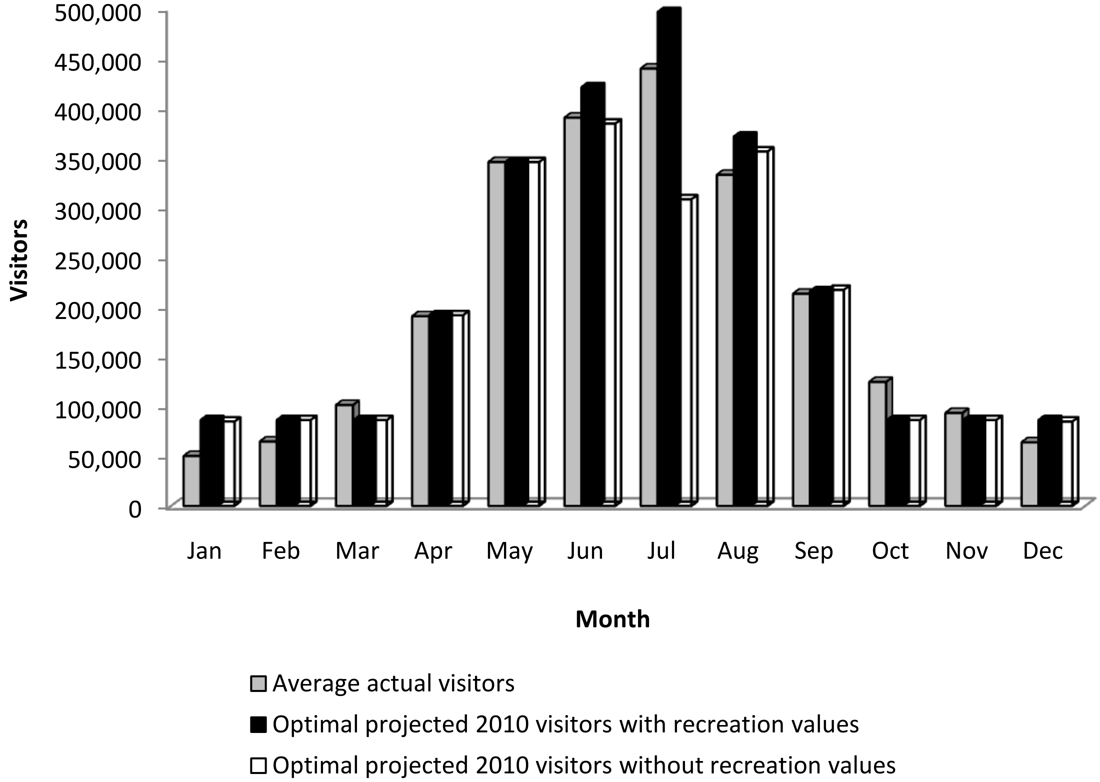

Figure 11.-Comparison of optimal number of monthly visitor for Lake Tenkiller when recreational benefits were and were not included in the objective function for the year 2010 with the average historical monthly visitors.