AN ECONOMIC ANALYSIS OF SELECTED STRATEGIES FOR DISSOLVED OXYGEN MANAGEMENT: CHATTAHOOCHEE RIVER, GEORGIA

U.S. GEOLOGICAL SURVEY,

Open-File Report 79-412

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1979

UNITED STATES DEPARTMENT OF THE INTERIOR

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ABSTRACT

Using the Chattahoochee River as an example, a method for evaluating the cost-effectiveness of alternative strategies for dissolved oxygen (DO) management is demonstrated. The conceptual framework for the analysis is suggested by the economic theory of production. The minimum flow of the River and the percentage of the total waste inflow receiving nitrification are considered to be two variable inputs to be used in the production of a given minimum concentration of DO in the River. Each of the inputs has a cost: the loss of dependable peak hydroelectric generating capacity at Buford Dam associated with flow augmentation and the cost associated with nitrification of wastes. The least-cost combination of minimum flow and waste treatment to achieve a prescribed minimum DO concentration is identified.

Results indicate that, in some instances, the waste assimilative capacity of the Chattahoochee River can be substituted for increased waste treatment with the associated savings in waste treatment costs more than offsetting the benefits foregone due to the loss of peak generating capacity at Buford Dam. The sensitivity of the results to the estimates of the cost of replacing peak generating capacity is examined. It is also demonstrated that a flexible approach to the management of DO in the Chattahoochee River may be much more cost-effective than a more rigid, institutional approach wherein constraints are placed on the flow of the River and/or waste treatment practices.

Introduction

This study has two primary purposes: (1) to demonstrate a method of evaluating the cost-effectiveness of alternative strategies for the management of the concentration of dissolved oxygen (DO) in a river; (2) to demonstrate how the results of a U.S. Geological Survey (USGS) River Quality Assessment can be applied, within the context of economic analysis, to a DO management problem. Results of the USGS Chattahoochee River Quality Assessment are utilized to estimate the costs associated with selected strategies for maintaining three different minimum DO concentrations in the Chattahoochee River between Atlanta and West Point Lake.

Nature of the Problem

During 1977, the dissolved oxygen (DO) concentration in the Chattahoochee River at Fairburn, Georgia, (25 miles downstream of Atlanta) was less than 5.0 mg/L 10 percent of the time (Stamer and others, 1978). The periods of low DO concentrations occurred primarily in the summer and autumn. During October, the DO concentration was below 5.0 mg/L 31 percent of the time--more than any other month.

The occurrences of low DO concentrations correspond closely with the occurrences of low discharge in the River. This relationship can be seen in Figure 1 which shows (top) the average daily DO concentration at Fairburn and (bottom) the average daily discharge at Atlanta--which is about 1.5 days travel time upstream of Fairburn.

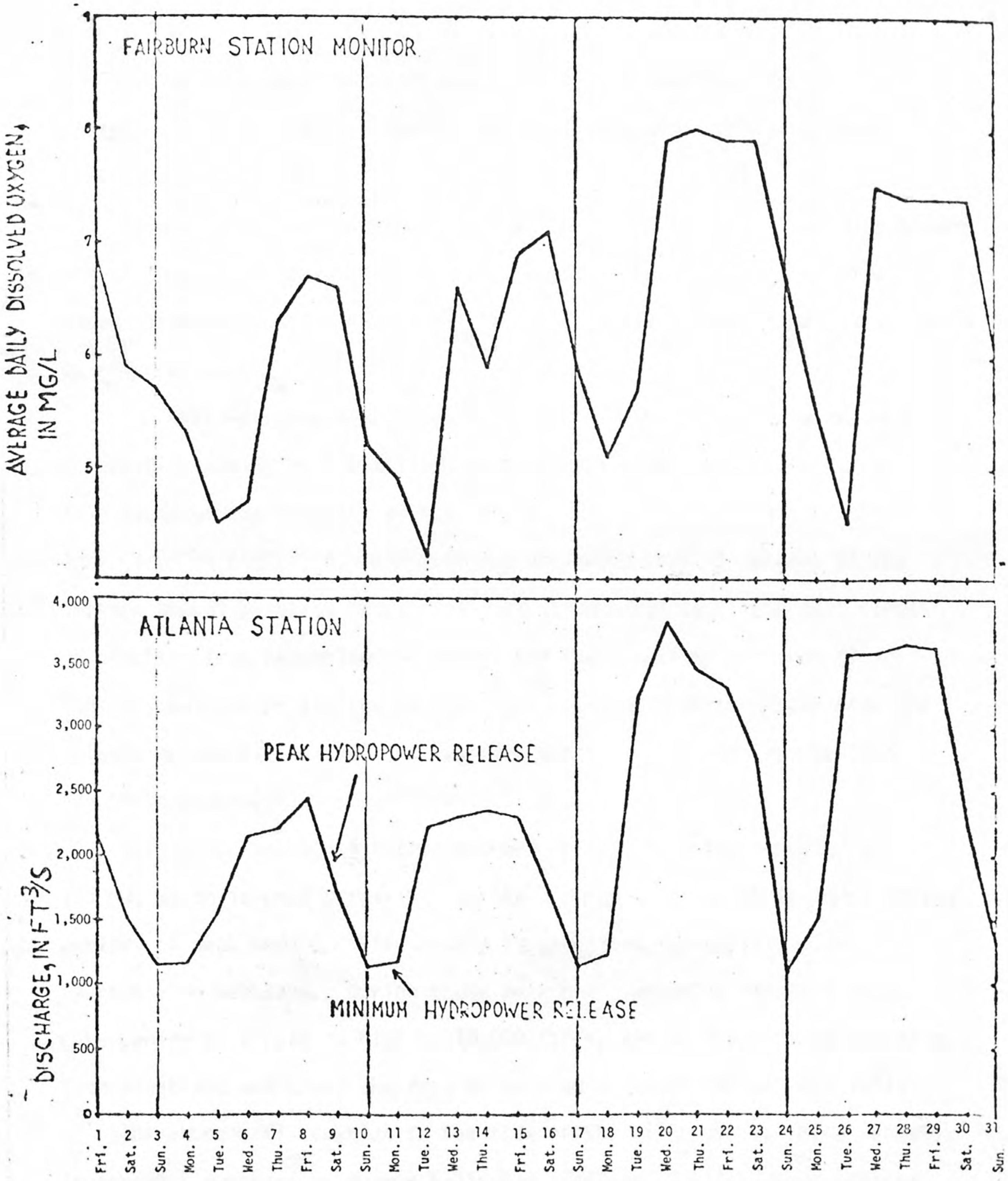


Figure 1.--Dissolved oxygen concentrations at the Fairburn station monitor and mean daily discharge at the Atlanta station during July 1977

Buford Dam

Both graphs in Figure 1 display a 7-day periodicity. The periodicity of the Atlanta hydrograph is a consequence of the pattern of releases at Buford Dam.

Figure 2 is a schematic map of the Chattahoochee River. In this figure, the various impoundments, gages, water supply withdrawal points and waste-water discharge points of interest in this study are identified and located by river mile.

The multi-purpose Buford Dam impounds Lake Sydney Lanier which has a storage capacity of 1.9 million acre-feet at normal pool elevation. In a study of the benefits of the Buford Dam/Lake Lanier project (U.S. Army Corps of Engineers, 1977), it was estimated that 74 percent of the average annual benefits consist of recreation benefits, 17 percent consist of benefits from hydroelectric power, and the remainder are from flood control, navigation (in the Apalachicola waterway), water supply (for the Atlanta metropolitan area) and low flow/water quality maintenance (for the Chattahoochee River from Atlanta to West Point Lake).

Buford Dam has an installed hydroelectric generating capacity of 105 MW, which is used primarily for the production of electric power during periods of peak demand. Electricity is generated, primarily, about 6 hours/day on weekdays. During these peak hours water is released from Lake Lanier at a rate as high as 10,000 ft^3/s, and at other times (morning, late night and weekends) the rate of release is approximately 600 ft^3/s.

The extreme fluctuation in the flow of the river due to these releases is somewhat dampened by Morgan Falls Dam, located 10 miles above Atlanta, and by the natural attenuation of the flood wave over the 46 miles between

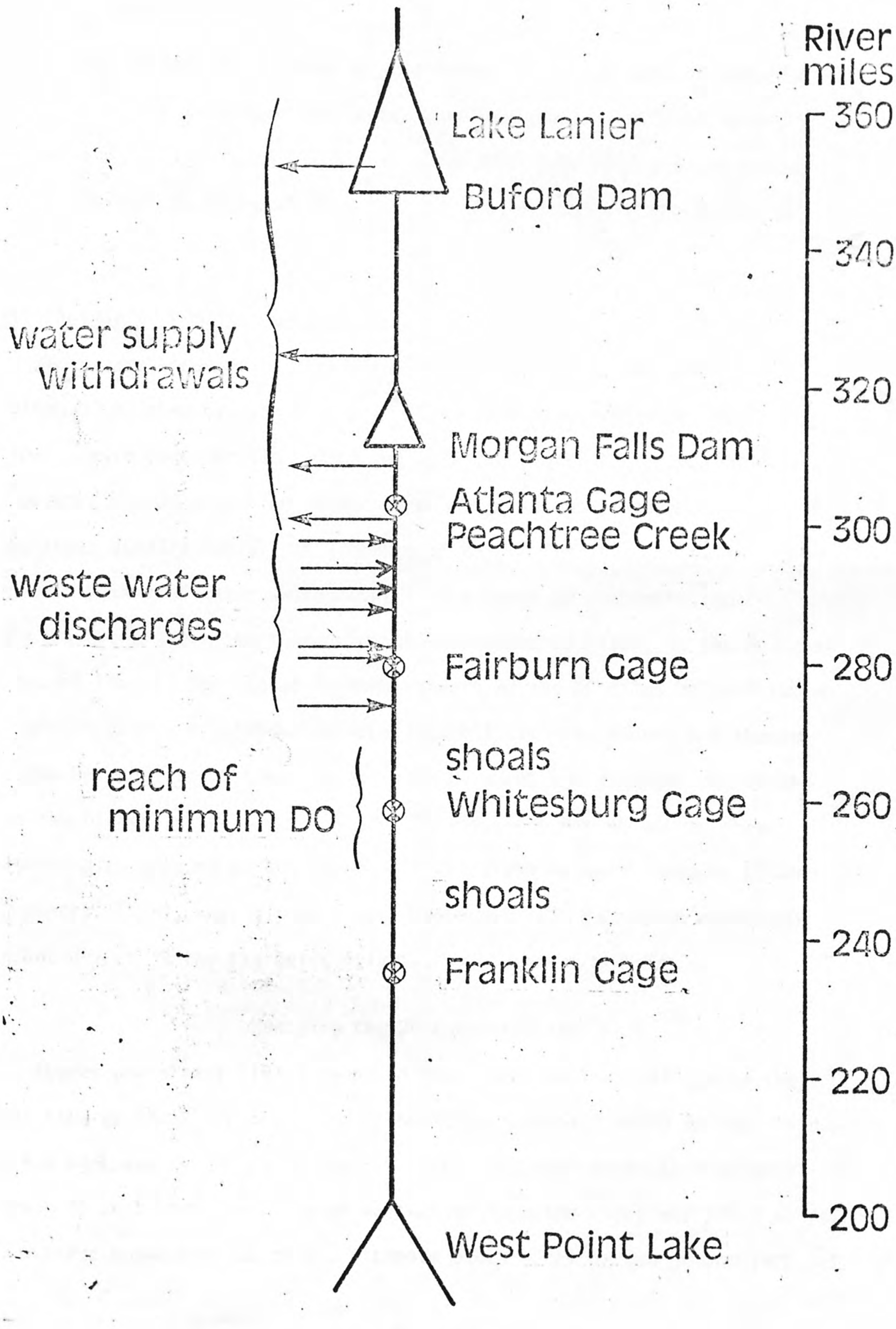


Figure 2.--Schematic map of the study reach of the Chattahoochee River

Buford Dam and Atlanta. There is some tributary inflow between Buford Dam and Atlanta, but there are also water supply withdrawls in this reach. Low release rates at Buford Dam that occur from late Friday night through mid-day Monday are somewhat mitigated but very evident in the Sunday and Monday flows at Atlanta.

Relationship of Flow and DO

There are three mechanisms whereby river discharge may affect the minimum DO in the river. The first is dilution: higher discharge causes a lower waste concentration which results in a higher DO concentration throughout the DO sag. The second is a change in re-aeration: higher discharges usually cause less exchange of oxygen from the air to the water per unit volume of water which results in a lower DO concentration throughout the sag. The third, in the Chattahoochee River, is the decrease in travel time to the shoals located between 30 and 50 miles below Atlanta: the shoals have a pronounced re-aerating ability. The sooner the shoals are reached the less the wastes are able to exert their oxygen demand and thus the higher is the minimum on the DO sag. The net effect of these relationships appears to be, both empirically and in model results (Stamer and others, 1978), that higher river discharges lead to higher minimum DO concentrations in the sag below Atlanta.

Managing the DO Concentration

Stamer and others (1978) reported that, on June 1-2, 1977, when the river flow at the Atlanta gage was 1150 ft^3/s, the minimum DO in the river was 4.0 mg/L and the DO was below 5.0 mg/L along approximately a 20 mile reach. At that time, the flow of wastewater into the river was 185.3 ft^3/s. The average concentration of the ultimate biochemical oxygen demand (BOD_u)of the wastewater was 44 mg/L, and the average ammonia nitrogen concentration was 11 mg/L. A model developed by Stamer and others (1978) predicts that, under anticipated conditions for the year 2000 and with secondary waste treatment (370 ft^3/s of wastewater, BOD_u concentration of 45 mg/L and an ammonia nitrogen concentration of 15 mg/L) the minimum DO concentration given the same river flow would be 1.1 mg/L and the DO concentration would be below 5.0 mg/L along a 50 mile reach. This model also predicts the change in the minimum DO given a change in the flow at Atlanta. For example, if the flow were 1800 ft^3/s instead of 1150 ft^3/s in 2000, the minimum DO concentration would, it is predicted, be 2.6 mg/L and a reach of 43 miles would have a DO concentration below 5.0 mg/L.

The model developed by Stamer and others (1978) also predicted minimum DO concentrations given other degrees of waste treatment. For example, if the BOD_u concentration of the waste effluent were 15 mg/L rather than 45 mg/L and the ammonia nitrogen concentration 5 mg/L rather than 15 mg/L, the minimum DO concentration would be 5.1 mg/L rather than 2.6 mg/L given a flow at Atlanta of 1150 ft^3/s.

These model results clearly indicate that both modification of the hydrograph at Atlanta and modification of waste inputs from treatment plants located just below Atlanta are possible approaches to manipulating the present and future DO concentrations in the Chattahoochee River.

The Range of Alternatives

There are, conceptually, a number of techniques that might be used, alone or in combination, to manage the DO concentration in the Chattahoochee River. The techniques include:

1. Improved sewage treatment, so that less water is required in the Chattahoochee River for water-quality maintenance purposes.

2. Construction of a sewage storage facility to hold the sewage for release during peak flows of the river.

3. Construction of a water-supply storage facility so as to permit increased withdrawals from the river during peak flow periods for use during low flow periods. This would leave more water available for water-quality maintenance during low flow periods.

4. Develop sources of water supply outside of the Chattahoochee River basin so that more water could be available for water-quality maintenance.

5. Reduce the rates of water use (and, thus, sewage discharge)--especially during low flow periods. This could be accomplished by a number of rationing and/or water-pricing schemes.

6. Dredge Morgan Falls Reservoir so as to increase its capacity, and thus permit a more steady flow of the Chattachoochee River at Atlanta without affecting the dependable peaking capacity of Buford Dam.

7. Construct a reregulation structure (dam and reservoir) between Buford Dam and Morgan Falls Dam so as to permit a more steady flow at Atlanta.

8. Change the operating procedure of Buford Dam so as to release less water (and generate less electricity) during periods of peak demand for electricity and release more water at other times.

The full range of these techniques, both separately and in various combinations, may warrant consideration in the selection of an efficient method of improving the water quality of the Chattahoochee River below Atlanta.

The Alternatives Considered

To reduce this study to a manageable size given the resources available, only the following techniques are considered (separately and in combination) herein:

1. Add nitrification to the treatment process at some or all of the treatment plants discharging into the Chattahoochee River or its tributaries between

Atlanta and Whitesburg. The effluent concentrations given secondary treatment are assumed to be 45 mg/L BOD_u and 15 mg/L NH_4-N. Adding nitrification is assumed to result in concentrations of 27 mg/L BOD_u and 3 mg/L NH_4-N.

2. Dredge Morgan Falls Reservoir and construct a reregulation structure between Buford Dam and Morgan Falls Dam.

3. Change the operating procedure of Buford Dam so as to give explicit consideration to the release of water from Lake Lanier for water-quality maintenance purposes.

There are, of course, monetary costs associated with the first and second techniques. Also, a change in the operation of Buford Dam may entail changes in the benefits presently derived from that project. There may be changes in the pool elevation of Lake Lanier which would affect recreation benefits and the amount of electrical energy produced per unit volume of water released. There may be changes in the relative proportion of high-valued peak power and lower valued non-peak (or base) power. Most importantly, as more water is reserved for low flow maintenance less water is dependably available for peak power generation and there may be changes in the dependable peaking capacity of the generators at Buford Dam. The loss of this dependable peaking capacity will, it is assumed, entail the construction of peaking facilities elsewhere. Any change in the sum of these benefits as a result of a change in the operation of Buford Dam for water-quality maintenance purposes is considered to constitute a cost incurred for that purpose.

In this study, an attempt is made to identify the least-cost combination of the above three measures (nitrification, change in the operation of Buford Dam for water-quality maintenance, and improved re-regulation) that will achieve a given level of water quality as measured by the DO concentration in the Chattahoochee River. The least-cost combination of the three techniques are identified for three DO concentrations standards, 3, 4, and 5 mg/L, to obtain estimates of the cost (in terms of increased treatment costs and benefits foregone) of achieving different DO concentrations in the River below Atlanta.

Also, the quantity of waste discharged in the River will increase, with the population of the Atlanta region, over time. Thus, for any given level of waste treatment and DO standard, the water required for water-quality maintenance will increase with time. For this reason, separate estimates of the costs of the least-cost combination of the three techniques are presented for the years 1980, 1990, and 2000.

Estimates of the costs do not include any change in the flood control, navigation, and downstream hydroelectric power generation benefits as a result of a change in the operation of Buford Dam. Because the changes in operation considered are relatively minor, involving no change in the volume of the flood pool, no change in flood control benefits would be expected. Navigation and downstream hydroelectric power benefits would change only as a result of a major change in the seasonal pattern of releases from Buford Dam. The changes in operation of Buford Dam contemplated herein are substantial at the time scale of hours and days but not at the time scale of seasons. The only costs considered are the change in the benefits associated with recreation on Lake Lanier and generation of electric power at Buford Dam, the cost of adding nitrification to secondary waste treatment facilities, and the cost of constructing and dredging reregulating facilities.

Just as there are costs incurred in achieving or maintaining a given level of water quality in the Chattahoochee River, there may also be benefits from so doing. Economic efficiency criteria state that the net benefits to be obtained from an increase in the DO concentration of the River will be a maximum at that level of concentration where the cost of providing the last increment of DO concentration (for example, to 4.6 mg/L from 4.5 mg/L) is just equal to the benefits to be obtained by improving the DO concentration by that amount. Estimation of the benefits to be obtained by improving the DO concentration of the river is beyond the scope of this study, and no attempt is made to identify that level of DO concentration which will maximize net benefits.

Study Overview

In the next section is described the model used to relate the minimum flow of the Chattahoochee River at Atlanta, the proportion of the wastes discharged which receive nitrification, and the DO concentration in the Chattahoochee River below Atlanta. This model provides estimates of the combinations of minimum flow at Atlanta and nitrification which will provide a given minimum DO concentration in the River.

Next is described a hydrologic simulation model which relates the flow of the Chattahoochee River at Atlanta and the pool elevation of Lake Lanier with the operation and dependable hydroelectric peaking capacity of Buford Dam. This model also provides estimates of the maximum sustainable minimum flow at Atlanta, and thus delimits the combinations of minimum flow and nitrification which are potentially capable of producing a given minimum DO concentration in the River.

Then, the methods used to obtain estimates of the change in hydroelectric power and recreation benefits and of the waste treatment costs are described. Following this, the method of identifying the least-cost combination of additional waste treatment (nitrification) and flow augmentation is described. Finally, the sensitivity of the least-cost combination to the estimate of the cost of replacing peak generating capacity is explored and an analysis of the consequences of certain institutional constraints on the cost of attaining a given DO concentration is provided.

This study does not represent an attempt to prescribe either specific operating rules for Buford Dam or a specific waste treatment plan for the Atlanta Region. This study only provides an examination of the relationship (or trade-off) between the use of the Lake Lanier/Chattahoochee River waters for enhancement of its DO concentration on the one hand and hydro-electric power generation on the other. That is to ask: To what extent can the waste assimilative capacity of the River be substituted for an increased waste treatment with what concomitant decrease in treatment costs and at what cost, if any, in terms of hydroelectric power and recreation benefits foregone? This question is explicitly posed and one scheme for exploring it is presented herein.

The Dissolved Oxygen Model

Stamer and others (1978) describe a dissolved oxygen model (DOM) of the Chattahoochee River from the Atlanta gage (river mile 302.97) to the Franklin gage (river mile 235.46). This model is used herein to estimate the minimum DO concentration in this reach as a function of (1) the minimum flow at the Atlanta gage (Q_A) and (2) the percentage (P) of total wastes receiving nitrification in addition to secondary treatment at the sewage treatment plants along the reach.

Model runs were conducted for three different years (1980, 1990, and 2000) because of differences among years in the total volume of wastewater that is expected to be discharged to the river. In table 1 is given the name, location (river mile) and expected flow rate for each of the sewage treatment plants along the reach. The estimates of the wastewater flow rates were based on information published by the Atlanta Regional Commission (Atlanta Regional Commission, 1977). All wastewaters are assumed to have a DO concentration of 6 mg/L when discharged from the treatment plants.

In the model, it is assumed that, at the Atlanta gage, the Chattahoochee River has a BOD_u concentration of 4.0 mg/L, an ammonia nitrogen concentration of 0.02 mg/L and DO at its saturation concentration of 9.3 mg/L. The tributary BOD_u concentrations range from 3.0 mg/L to 7.0 mg/L, ammonia nitrogen concentrations from 0.01 mg/L to 0.12 mg/L, and DO concentrations are assumed to be at or near saturation. River water temperatures range from 20.8° C to 27.1° C. All of these temperature, BOD_u, ammonia, and DO values are based on those observed in June, 1977.

Table 1.--The expected average daily flow from waste treatment plants discharging to the Chattahoochee River between Atlanta and Whitesburg: 1980, 1990, 2000.

Plant Name	River Mile	Expected Average Daily Flow (ft^3/s) 1980	1990	2000
Cobb-Chattahoochee	300.56	24	29	31
R.M. Clayton	300.24	131	150	161
South Cobb	294.78	38	51	48
Utoy Creek	291.60	42	46	44
Sweetwater Creek	288.57	—	3	3
Camp Creek	283.78	15	22	27
Annewakee Creek	281.46	—	6	6
Regional Interceptor	281.45	—	—	42
Bear Creek	274.48	—	7	8

The model assumes steady flow conditions. Stamer and others (1978) verified that, even though the flows in this reach are often quite unsteady (see figure 1), their model provides a satisfactory representation of the DO system in a given "parcel" of water as it moves downstream.

Taking 1990 as an example, 14 different runs of the DOM were conducted so as to provide a basis for the development of a general expression of the relationship between Q_A, P, and minimum DO concentration in the Chattahoochee River.

A typical run may be described as follows: The flow at the Atlanta gage (rm 302.97) is 1800 ft^3/s. The Atlanta Water Works (rm 300.62) withdraws 109 ft^3/s, leaving a flow of 1691 ft^3/s to the confluence of the Chattahoochee River and Peachtree Creek (rm 300.52). Over the next 26.14 miles from this point, there are eight wastewater treatment plants discharging effluent at the rates specified in table 1. The total flow from these plants is 314 ft^3/s. In addition, there is a total of 93 ft^3/s of tributary flow (the 7-day, 10-year, low flow of each tributary) entering the mainstem over the 65 miles between Peachtree Creek and the Franklin gage. Thus, the flow along the entire reach varies from 1800 ft^3/s down to 1691 ft^3/s and back up to 2098 ft^3/s at the downstream end.

In the particular model run being considered here, seven of the eight treatment plants are assumed to employ only secondary treatment, while the R.M. Clayton plant (rm 300.24) employs nitrification in addition to secondary treatment. The flow from the R.M. Clayton plant is predicted to be 150 ft^3/s in 1990, while the total flow from all eight plants is predicted to be 314 ft^3/s. Thus, 48 percent of the wastes receive nitrification (P = 48).

Given that Q_A is set at 1800 ft^3/s and that P = 48, the model results show a minimum DO concentration of 5.0 mg/L in the study reach.

Another run of the DOM was conducted, identical to the run just described except that the flow at the Atlanta gage was 850 ft^3/s (resulting in a flow at Peachtree Creek of 741 ft^3/s and a flow at the Franklin gage of 1148 ft^3/s). Given a Q_A of 850 ft^3/s and that P was set at 48, the model estimated a minimum DO concentration of 2.8 mg/L.

According to Stamer and others (1978), the relationship between minimum DO and flow at Atlanta is very nearly linear (see figure 3). Thus the results of the two model runs just decribed may be summarized by an equation of the form:

$$a \cdot Q_A + b = D,$$

where Q_A is the minimum flow at the Atlanta gage in ft^3/s and D is the minimum DO over the reach in mg/L. The equation may be considered valid only for Q_A values in or near the range of 850 ft^3/s to 1800 ft^3/s. Inserting the appropriate values for the slope (a) and intercept (b) results, for the example described, in:

$$.0023 \cdot Q_A + .89 = D$$

Results from the DOM

Pairs of runs (one for Q_A = 1800 ft^3/s, the other for Q_A = 850 ft^3/s) similar to the two just described were conducted for a total of seven different cases. In each of these cases, the combination of treatment plants with only secondary treatment and with secondary treatment plus nitrification (that is the value of P) was varied. The results of these 14 runs are presented in the two graphs depicted in figure 4. In figure 4a, the slope parameter (a) is

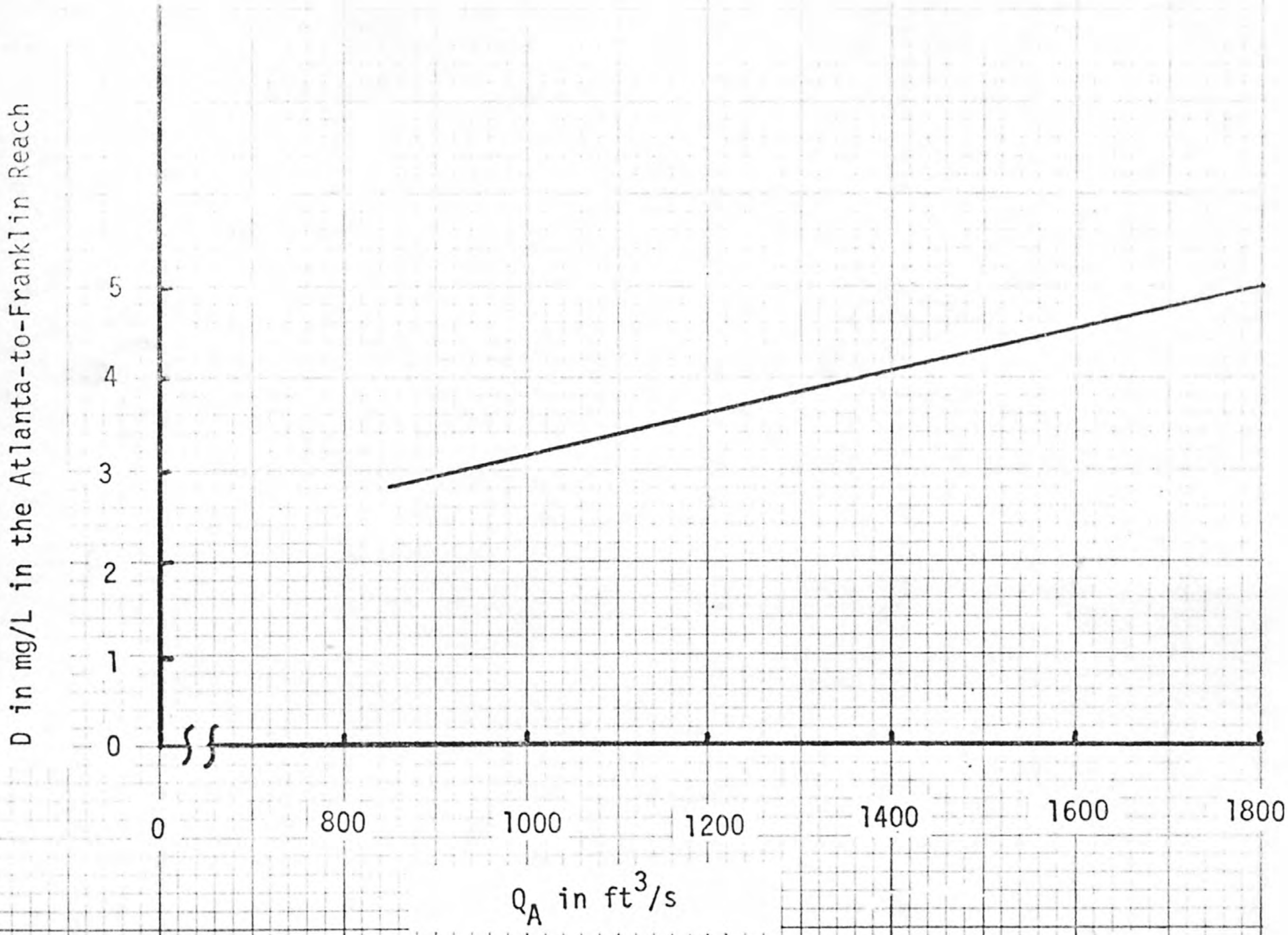
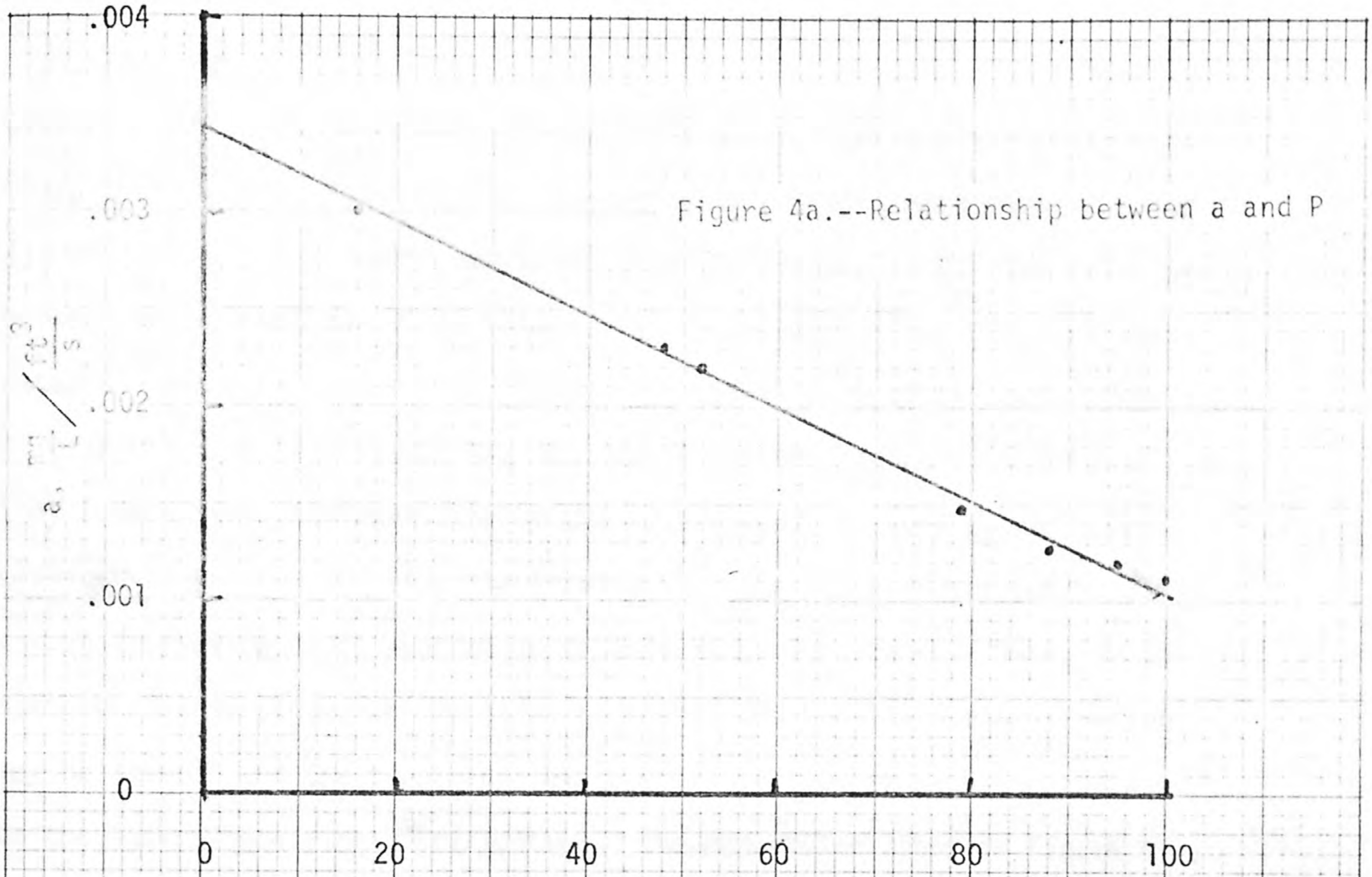


Figure 3.--Minimum DO concentration (D) in mg/L as a function of flow at the Atlanta gage (Q_A) in ft^3/s given that 48 percent of the waste flow receives nitrification; 1990 conditions.



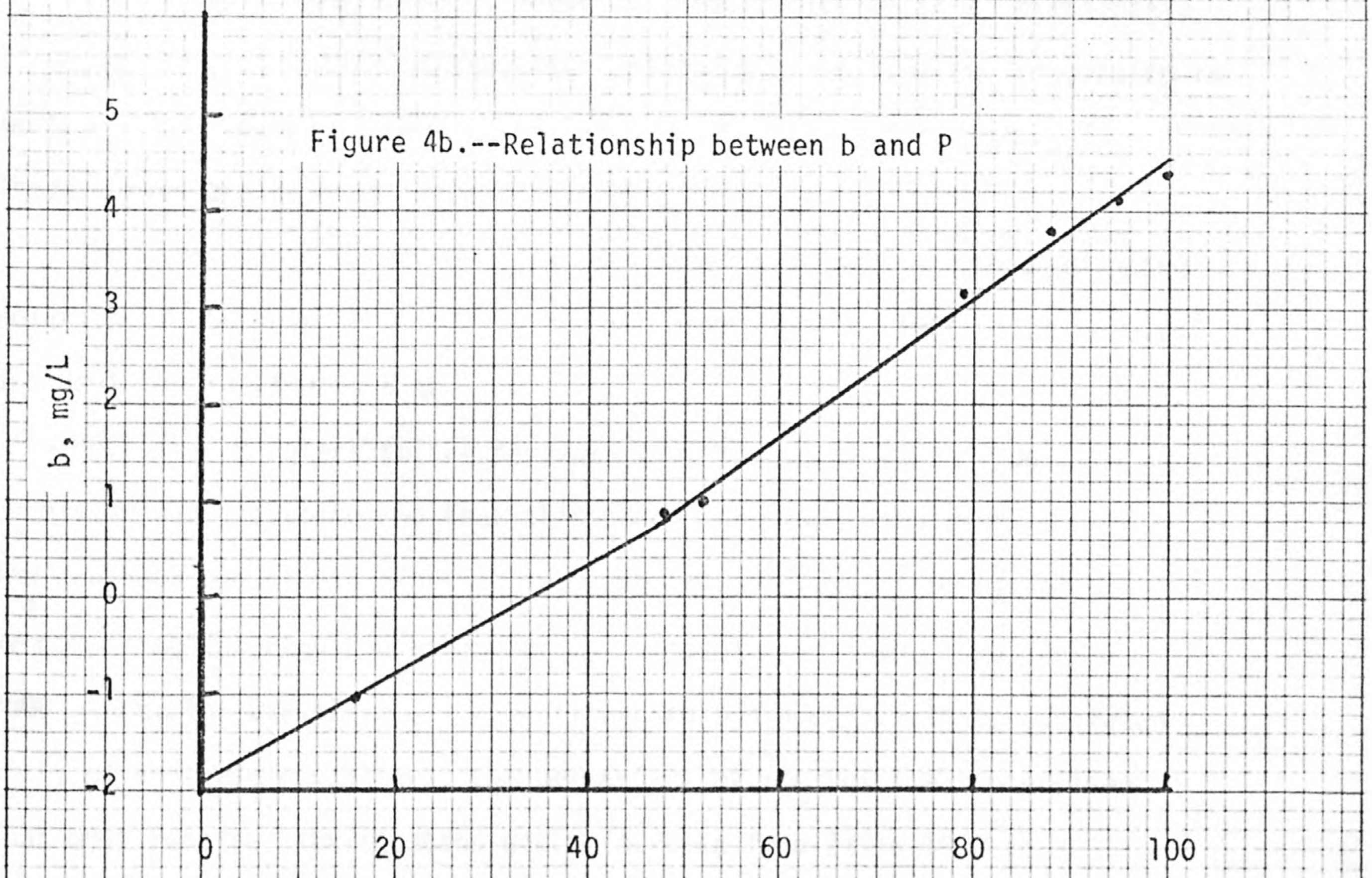


Figure 4.--Relationship of parameters of $aQ_A + b = D$ to percentage of total waste flow receiving nitrification (P).

plotted against the percentage of the total waste flow receiving nitrification (P). In figure 4b, the intercept parameter (b) is plotted against P. These figures suggest that both a and b are strongly related to P. The relationship between a and P was expressed by a linear regression (R^2 = .99), and that between b and P by a piecewise linear regression (each of the two regressions of b on P had an R^2 = .99). The implication of these good fits (high R^2) is that P is a very good predictor of the relationship between Q_A and D as provided by the DOM and that the locations of those sewage treatment plants chosen to provide nitrification is of only minor importance. Thus, in the context of this study, the location of the plants providing nitrification may be ignored and the treatment levels characterized by P-the percentage of the wastes receiving nitrification. The regression lines in figure 4 thus describe the relationship between Q_A, D, and P.

Figure 6 provides a useful graphical description of this relationship. It shows the combination of treatment (P) and minimum flow (Q_A) necessary to achieve a minimum DO concentration (D) of either 3, 4, or 5 mg/L. These curves are denoted "iso-DO" curves.

The same procedure as that just described was used to approximate the relationship between D, P, and Q_A for the year 1980 and 2000. The results are depicted in figures 5 and 7.

Note that P refers to the percentage of the total waste flow receiving nitrification and that this total increases with time. The consequences of the expected increase in wastewater flow can be seen by comparing the required amount of nitrification in 1980, 1990, and 2000 given, for example, Q_A = 1500 ft^3/s and D = 4 mg/L. It is estimated that, given these conditions, the percentage of the total waste effluent that must receive nitrification would increase from 22 in 1980 to 36 in 1990 to 48 in 2000. Since the total waste flow is increasing,

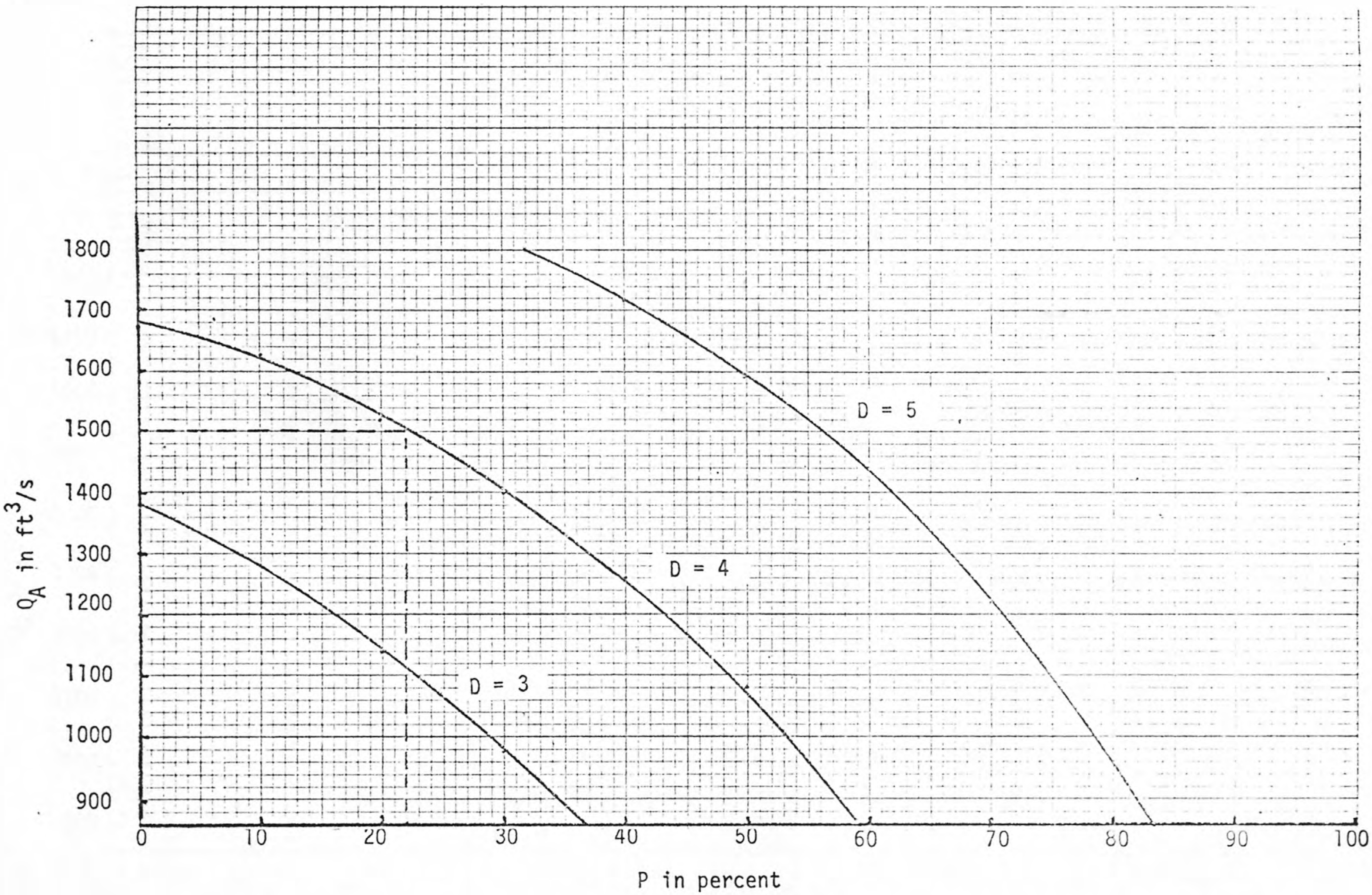


Figure 5.--Iso-DO curves showing combinations of P and Q_A that are predicted to result in minimum DO concentrations (D) of 3, 4, and 5 mg/L: 1980 conditions.

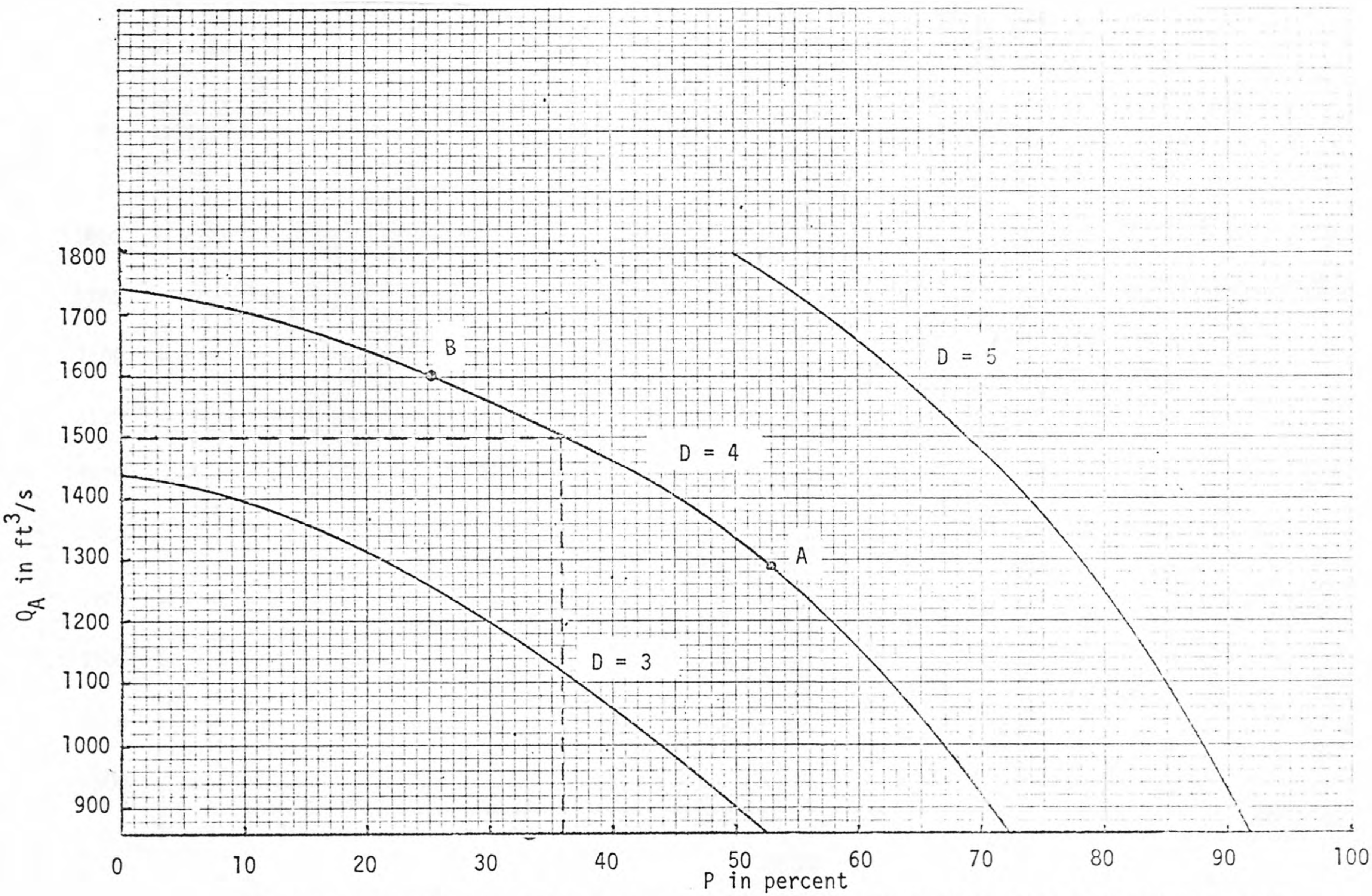


Figure 6.--Iso-DO curves showing combinations of P and Q_A that are predicted to result in minimum DO concentrations (D) of 3, 4, and 5 mg/L: 1990 conditions.

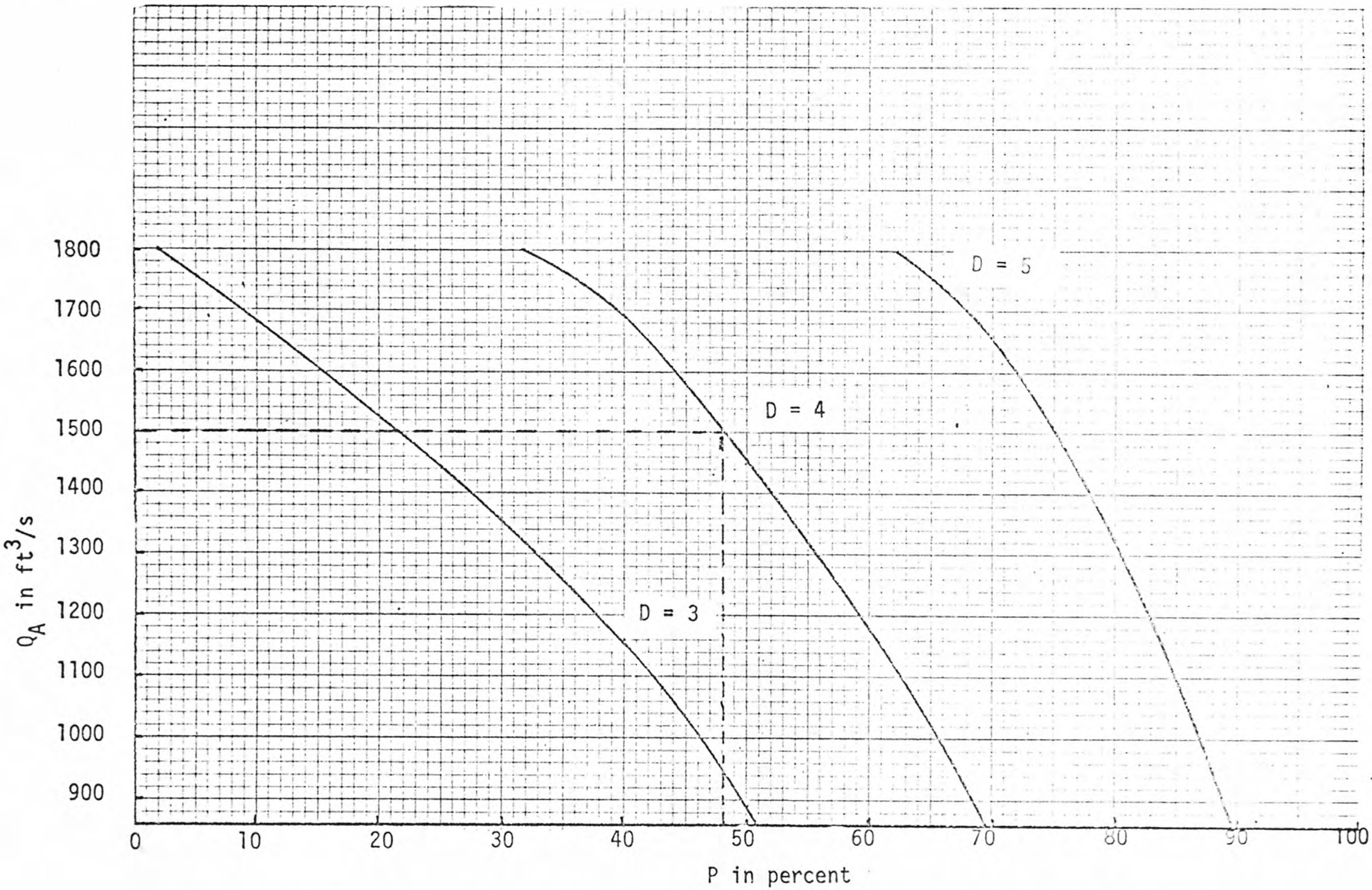


Figure 7.--Iso-DO curves showing combinations of P and Q_A that are predicted to result in minimum DO concentrations (D) of 3, 4, and 5 mg/L: 2000 conditions.

this means that the flow receiving nitrification would have to be 55 ft^3/s (0.22 x 250) in 1980, 113 ft^3/s (0.36 x 314) in 1990, and 179 ft^3/s (0.48 x 373) in 2000.

Given any minimum DO standard (D^*), the combination of P and Q_A selected must lie on (or above) the iso-DO curve representing D^* mg/L. But, not all combinations of P and Q_A along these iso-DO curves are technically feasible. For example, from figure 5, setting Q_A equal to 1800 ft^3/s and P equal to 50 will provide a minimum DO concentration of 5 mg/L in 1990. As will be seen, it is not possible to sustain this minimum flow at Atlanta under all hydrologic conditions. In addition, it is necessary to associate a cost with each combination of P and Q_A so as to permit identification of the least-cost combination. This cost is related, in part, to the minimum flow at Atlanta which, in turn, is related to the operation of Buford Dam. The hydrologic sumulation model (HSM) used both to identify the feasible values of Q_A and to provide a basis for estimating the costs (benefits foregone) associated with these values is presented in the next section.

The Hydrologic Simulation Model

The HSM was developed to determine, under a set of assumptions which shall be specified, the pattern of releases from Lake Lanier that are necessary to achieve a given dependable minimum flow at the Atlanta gage (Q_A). The pattern of release has effects on the benefits associated with each of the project purposes, and the HSM is designed to provide a basis for estimating the change in the project benefits as a result of a change in the pattern of release.

The key relationship that the HSM describes is that between the dependable minimum flow at Atlanta and the dependable hydroelectric peak generating (peaking) capacity of Buford Dam. The "amount" of each of these "products" that can be dependably provided by the Buford Dam project is a function of the inflows to Lake Lanier and tributary flows above Atlanta over an extended (at least two-year) drought.

The meaning of the word "dependable" is of paramount importance to an understanding of the HSM. Dependable minimum flow (peaking capacity) is defined as that rate of flow (peaking capacity) which can be provided at all times throughout a period in which the flows (both into Lake Lanier and tributary flow between Buford Dam and Atlanta) are those that occurred in the most severe extended drought in the historic record (of 49 years). This was a 132 week period comprising June 1954 through December 1956. As there is no reason to believe that a more severe drought will not occur in the future, that which is defined as "dependable" herein may not be "dependable" in the future. Rather than attempt to estimate the probability of more severe droughts or justify this definition on some economic grounds, it is simply accepted on the basis that previous studies of the Buford Dam project and of the Chattahoochee River (U.S. Army Corps of Engineers, 1977; Atlanta Regional Commission, 1977) have relied on the same convention.

Operation of the Buford Dam Hydrolectric Generating Facility: Assumptions and Definitions

Though Buford Dam has an installed hydroelectric generating capacity of 105 MW, the rate of production of electrical energy varies with the pool elevation of the reservoir and the rate of flow of the water past the turbines; that is, it varies with the pattern of releases from Lake Lanier. The calculation of hydroelectric power production is based on the following formula (Joe DeWitt, U.S. Army Corps of Engineers, Savannah District, Oral Communication, 1978):

$$Pe = 82.645(0.12390 + 0.000925\ (E - 1055))\ Q,$$

where

Pe = power in kW

E = pool elevation in feet above sea level

Q = flow through the powerplant in ft^3/s.

It is assumed that all water released from Lake Lanier is used for the production of electric energy.

The HSM is designed to, first, pattern the release of water from Lake Lanier so as to maximize the dependable summer peak generating capacity of Buford Dam. Given that this has been accomplished, the model allocates the release of water within any given week so as to maximize the peak energy production. Both of these maximizations are conducted subject to the constraints that the given downstream water supply needs and minimum flow at Atlanta (Q_A) are satisfied.

Definitions:

Peak energy: All electric energy generated between 2 p.m. and 8 p.m. on weekdays

Non-peak base energy: All electric energy other than peak energy

Dependable peak generating (peaking) capacity: The minimum rate of electric energy production during the peak hours of the summer periods of the 132 week simulation period.

Summer: Early June (week 22) through late September (week 33).

To understand the design and assumptions of the HSM, it is helpful to first understand the intertemporal distribution of the demand for electric energy. The quantity of electric energy demanded generally reaches a peak during the afternoon and early evening on weekdays and falls to a low during the early morning hours and on weekends. Though the "height" of these peaks varies throughout the year, the peak demand for electric energy is typically the highest during the summer months. The electric utility companies attempt to maintain sufficient generating capacity to meet the maximum peak demand, which will typically occur during the afternoon or evening of a summer weekday.

Hydroelectric turbines are especially useful for peaking purposes as they require very little start-up time and can be brought on-line quickly. Because of this capability, the limited water available is not generally used to produce base power except when it is necessary to release water to meet downstream needs or to vacate the flood pool.

It is assumed, therefore, that the release of water from Lake Lanier is to be patterned so as to maximize the dependable summer peaking capacity of Buford Dam, for it is during the summer that the electric utility company which purchases power from the Dam (the Georgia Power Co.) is most likely to require maximum generating capacity. If no releases are necessary (for example, when tributary flows are high and the pool elevation of Lake Lanier is below 1070 feet above sea level), it is assumed that no base electric energy is produced. Consequently, it is assumed that Buford Dam provides no dependable base generating capacity.

Description of the HSM

The HSM is designed to answer the following question:

1. What is the range of minimum flows at the Atlanta gage (Q_A) that could have been achieved under the 1954-56 drought hydrology?

2. Given a minimum flow at Atlanta (Q_A), what plan of operation of Buford Dam will maximize the dependable peaking capacity of the Dam?

3. What is the dependable peaking capacity of Buford Dam given this plan and Q_A?

4. What is the peak and non-peak electric energy production given this plan and Q_A?

5. What is the history of pool elevations of Lake Lanier given this plan and Q_A?

The HSM is designed to find a plan of releases from Buford Dam and Morgan Falls for the 132-week period, which maximizes the dependable peaking capacity of Buford Dam, subject to the following flow and storage constraints:

$$\frac{dS_1}{dt} = T_1 - W_1 - Q_1 \quad (1)$$

$$Q_1 \leq 10{,}000 \quad (2)$$

$$S_1(t_o) = 8.35 \times 10^{10} \quad (3)$$

$$S_1(t_f) = 4.69 \times 10^{10} \quad (4)$$

$$S_1 \leq 8.35 \times 10^{10} \quad (5)$$

$$Q_1 + T_2 \geq W_2 \quad (6)$$

$$\frac{dS_2}{dt} = Q_1 + T_2 - W_2 - Q_2 \quad (7)$$

$$S_2(t_o) = 0 \quad (8)$$

$$S_2(t_f) \geq 0 \quad (9)$$

$$S_2 \leq 1.09 \times 10^8 \quad (10)$$

$$Q_2 + T_3 - W_3 \geq Q_A \quad (11)$$

Decision variables: all are time varying and defined as ≥ 0.

S_1 = Storage in Lake Lanier in ft^3

S_2 = Storage in Morgan Falls Reservoir in ft^3

Q_1 = Release from Buford Dam (Lake Lanier) in ft^3/s

Q_2 = Release and spill from Morgan Falls Dam in ft^3/s

Initial storage conditions: beginning of week 22, 1954:

$S_1(t_o)$ = Initial storage in Lake Lanier in ft^3

$S_2(t_o)$ = Initial storage in Morgan Falls Reservoir in ft^3

Final storage conditions, end of week 49, 1956

$S_1(t_f)$ = Final storage in Lake Lanier in ft^3

$S_2(t_f)$ = Final storage in Morgan Falls Reservoir in ft^3

Time Varying Model Parameters:

T_1 = Inflows to Lake Lanier in ft^3/s
(constant over a week, values are those used in Corps of Engineers, Lake Lanier Restudy).

T_2 = Tributary inflows between Buford Dam and Morgan Falls in ft^3/s (constant over the week, values equal 1/2 of the tributary flow values reported in the Corps of Engineers, Lake Lanier Restudy).

T_3 = Tributary inflows Morgan Falls to the Atlantic Gage in ft^3/s (constant over the week, values equal 1/2 of the tributary flow values reported in the Corps of Engineers, Lake Lanier Restudy).

W_1 = Withdrawals from Lake Lanier in ft^3/s (constant over week, varies with time of year and year of analysis, see table 1).

W_2 = Withdrawals from the Chattahoochee River, Buford Dam to Morgan Falls in ft^3/s (constant over week, varies with time of year and year of analysis, see table 2).

W_3 = Withdrawals from the Chattahoochee River, Morgan Falls to the Atlanta gage in ft^3/s (constant over week, varies with time of and year of analysis, see table 3).

Time Constant Model Parameter

Q_A = Minimum flow requirement at the Atlanta gage in ft^3/s

Explanation of Constraints:

(1) Continuity equation for Lake Lanier.

(2) Limitation on release from Buford Dam, 10,000 ft^3/s is the channel capacity below the dam.

(3) Initial storage conditions for Lake Lanier equal to initial storage for the same period in the Corps' Base Plan of Operation.

(4) Final storage conditions for Lake Lanier equal to final storage for the same period in the Corps' Base Plan of Operation.

(5) Capacity constraint for Lake Lanier, 8.35×10^{10} ft^3 corresponds to pool elevation of 1070 ft. above sea level (normal pool elevation).

(6) Flows in the Buford Dam to Morgan Falls reach must be greater than or equal to the withdrawals in the reach at all times.

(7) Continuity equation for Morgan Falls Dam.

(8)+(9) Initial and final storage in Morgan Falls Reservior (arbitrary).

(10) Capacity constraint on Morgan Falls storage.

(11) Flows at Atlanta gage must be greater than or equal to the specified minimum flow Q_A, at all times.

Results from the HSM

The results of any run of the HSM, where a run is specified by a choice of years (1980, 1990, or 2000) and a choice of Q_A values, are the values of the following variables:

1. End-of-week pool elevation for each week.
2. Release rate and power production for the 30 peak hours in each week.
3. Release rate and power production for the 72 non-peak weekday hours in each week.
4. Release rate and power production for the 66 weekend (non-peak) hours in each week.

These results are summarized as total non-peak energy, total peak energy, and dependable peaking capacity.

To illustrate the results of the HSM, two examples will be described. Both are based on estimated water supply withdrawals for the year 1990 (tables 2, 3, and 4). In the first case, the required flow at Atlanta (Q_A) is set at 1290 ft^3/s, and in the second case Q_A is set at 1600 ft^3/s. Two different weeks of operation will be considered in detail in this comparison: week 33, 1954 (mid-August) and week 40, 1954 (early October). In both weeks, the tributary flows (T_2 and T_3) are equal to zero. The releases and hydropower production under each run are given in table 5. The release pattern for these weeks are shown in figure 8.

Comparison of the two cases brings out two important points about the consequences of increasing the required minimum flow at Atlanta. The first is that the releases from Buford Dam are redistributed with respect to time of week: weekend flows increase and peak flows either decrease (if summer) or increase (if non-summer). The second point is that releases are redistributed with respect to time of year: weekly average flows during the summer season decrease and flows during the remainder of the year increase.

Table 2.--Withdrawals from Lake Sidney Lanier (ft^3/s).

Weeks	1980	1990	2000
1-13	12.6	23.6	77.3
14-17	13.3	24.9	81.9
18-22	14.0	26.2	86.0
23.26	14.7	27.5	90.2
27-35	15.5	29.0	95.3
36-39	14.0	26.2	86.0
40-44	13.3	24.9	81.9
45-52	12.6	23.6	77.3
Average	13.6	25.5	83.7

Table 3.--Withdrawals from Chattahoochee River; Buford Dam to Morgan Falls Dam (ft^3/s).

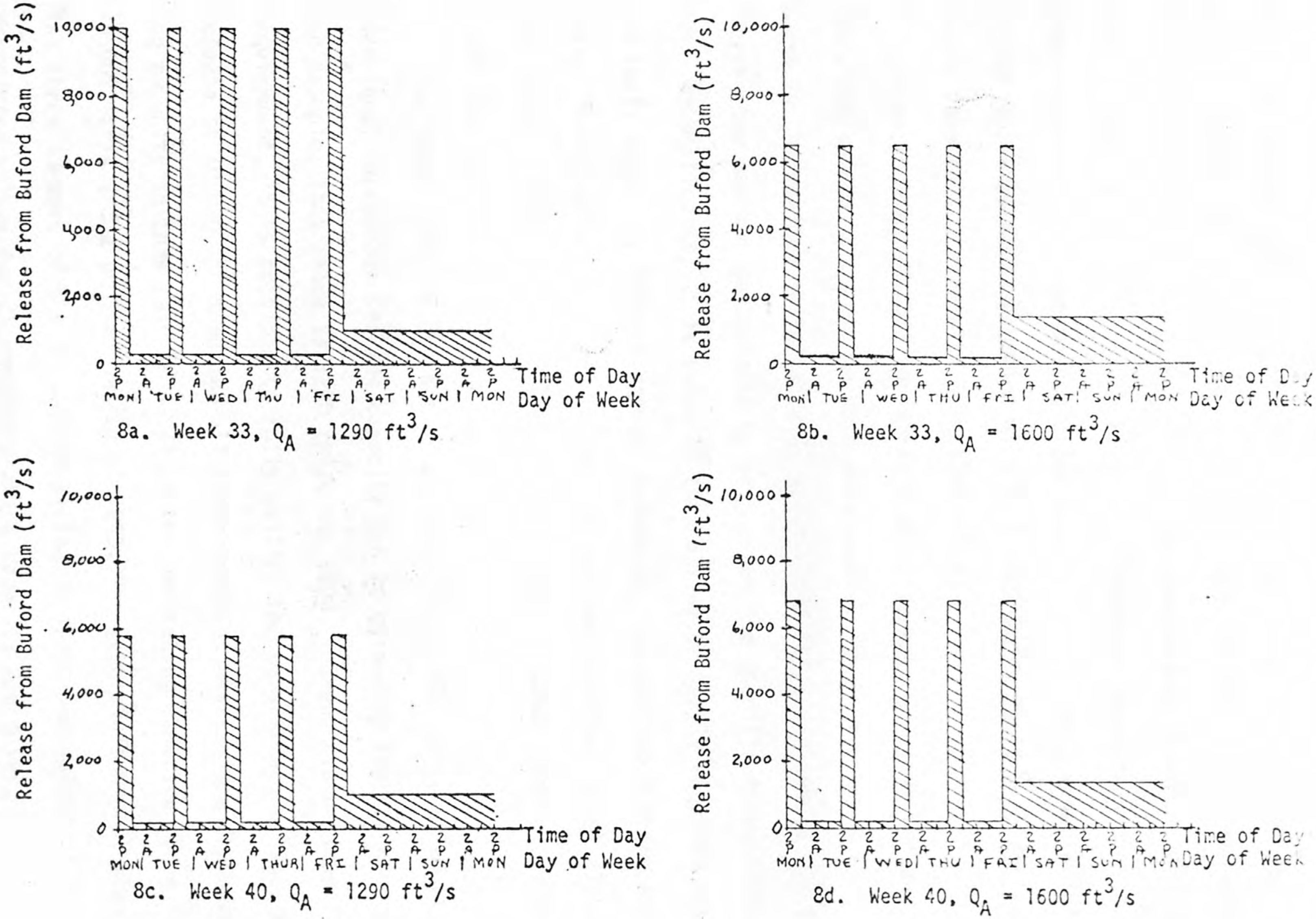
Weeks	1980	1990	2000
1-13	114.9	160.4	375.7
14-17	121.6	169.8	397.7
18-22	127.7	178.3	417.6
23-26	134.0	187.1	439.3
27-35	141.5	197.6	462.7
36-39	127.7	178.3	417.6
40-44	121.6	169.8	397.7
45-52	114.9	160.4	375.7
Average	124.3	173.6	406.6

Table 4.--Withdrawals from Chattahoochee River: Morgan Falls to the Atlanta gage (ft^3/s).

Weeks	1980	1990	2000
1-13	33.3	44.4	107.8
14-17	35.2	46.9	114.1
18-22	37.0	49.3	119.9
23-26	38.8	51.7	125.8
27-35	41.0	54.6	132.8
36-39	37.0	49.3	119.9
40-44	35.2	46.9	114.1
45-52	33.3	44.4	107.8
Average	36.0	48.0	116.7

Table 5.--HSM Results: 1990 conditions

Minimum flow at the Atlanta Gage	Q_A = 1290 ft^3/s	Q_A = 1600 ft^3/s
Week 33, 1954		
Average discharge (ft^3/s)	2,290	1,780
Discharge during peak hours hours (ft^3/s)	10,000	6,480
Discharge during non-peak hours weekdays (ft^3/s)	198	198
Discharge during weekends (ft^3/s)	1,070	1,380
Total electric energy production (MWh)	4,270	3,500
Peak energy production (MWh)	3,330	2,320
Non-peak energy production weekdays (MWh)	160	160
Non-peak energy production weekends (MWh)	780	1,020
Week 40, 1954		
Average discharge (ft^3/s)	1,510	1,820
Discharge during peak hours hours (ft^3/s)	5,760	6,810
Discharge during non-peak hours weekdays (ft^3/s)	170	170
Discharge during weekends (ft^3/s)	1,030	1,340
Total electric energy production (MWh)	2,720	3,360
Peak energy production (MWh)	1,860	2,250
Non-peak energy production weekdays (MWh)	130	130
Non-peak energy production weekends (MWh)	730	980



8a. Week 33, Q_A = 1290 ft^3/s

8b. Week 33, Q_A = 1600 ft^3/s

8c. Week 40, Q_A = 1290 ft^3/s

8d. Week 40, Q_A = 1600 ft^3/s

Figure 8.--Simulated releases at Buford Dam during weeks 33 and 40 of 1954, given a minimum flow at Atlanta (Q_A) of (1) 1290 ft^3/s and (2) 1600 ft^3/s; 1990 conditions.

In figure 9 is depicted the 132-week record of simulated pool elevations for these two cases. Given that Q_A is set equal to 1600 ft^3/s, the pool elevation varies less throughout each year and tends to be higher during the summer months. When Q_A is low, less water need be saved for flow maintenance in the autumn and thus more may be used for summer peak-power production. Consequently, a low Q_A will result in more reservoir draw-down during the summer recreation season than would a high Q_A. From the standpoint of recreation, a plan of operation with Q_A = 1600 ft^3/s has a more desirable result than does a plan with Q_A = 1290 ft^3/s.

After running the HSM for a range of different Q_A values for any given year, two values of Q_A emerge as having special significance. The first of these is the maximum sustainable Q_A value (1600 ft^3/s for 1990). It is, of course, the maximum sustainable Q_A only under the specific assumption of the HSM. In particular, it is required that all water supply requirements be met and that, under the 1954-56 drought hydrology, the minimum storage in Lake Lanier is not allowed to fall below 1.07 million acre-feet (pool elevation 1043.9 ft), which is 56 percent of the storage at normal pool elevation (1070 ft).

The other value of Q_A that is of interest is that value below which no additional dependable peaking capacity can be gained by further decreasing Q_A. For example, this value is 1290 ft^3/s for 1990. Given this minimum flow requirement, it is possible to fully utilize the generating turbines with a release of 10,000 ft^3/s during all summer peaking hours. The dependable peaking capacity in this case is equal to the generating capacity for a flow of 10,000 ft^3/s and a pool elevation of 1043.9 ft (the minimum pool elevation for the three summers of the simulation period). These two values of Q_A and the associated values for dependable peaking capacity are given, for each of the three years, in table 6.

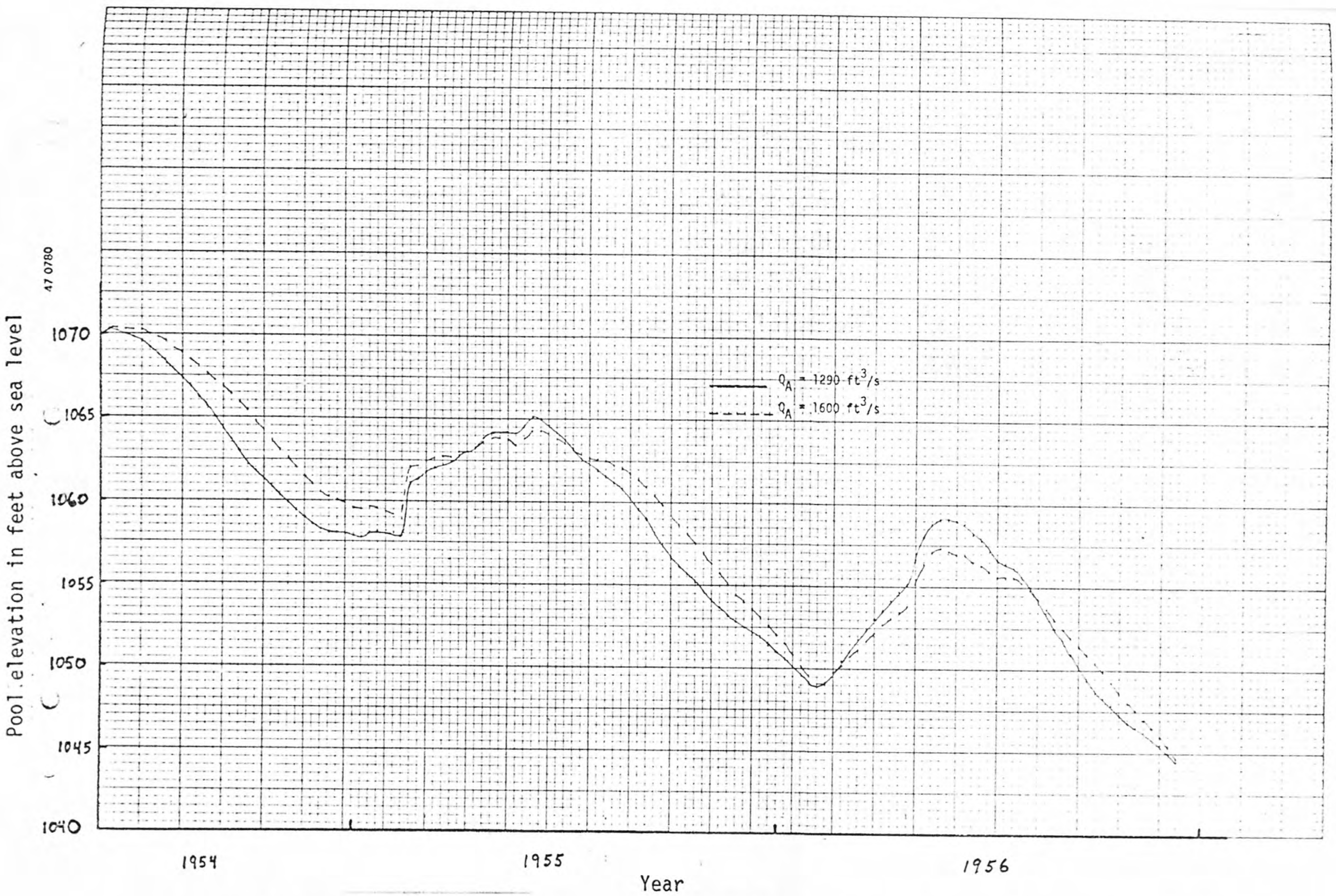


Figure 9.--Pool elevation of Lake Sydney Lanier over the period of simulation given that the minimum flow at Atlanta (Q_A) is set at (1) 1290 ft^3/s and (2) 1600 ft^3/s; 1990 conditions.

Table 6.--HSM Results

	1980	1990	2000
Maximum sustainable value of Q_A (ft^3/s)	1670	1600	1230
Dependable peaking capacity at maximum sustainable Q_A (MW)	66	66	58
Value of Q_A associated with maximum dependable peaking capacity (ft^3/s)	1380	1290	870
Maximum value of dependable peaking capacity (MW)	98	98	97

The HSM, then, was used to delimit the feasible range of Q_A as it identified the maximum sustainable Q_A. It also provided estimates of dependable peak generating capacity, weekly peak and non-peak power production and the weekly pool elevation of Lake Lanier upon which to base estimates of the change in benefits given a change in Q_A.

Estimation of Costs: Benefits Foregone and Waste Treatment Costs

In this section is described, first, the method used to obtain estimates of the recreation and hydroelectric benefits associated with a given Q_A under (1954-56) drought conditions. Then, it is argued that these drought-condition benefits are not representative of the benefits associated with any given Q_A under more nearly average hydrologic conditions, and the method used to approximate average annual benefits is described. These estimates of the benefits associated with a given Q_A permit estimation of the costs, in terms of benefits foregone, associated with a change in Q_A and, thus, with a change in the operation of Buford Dam.

Also described is the method used to obtain estimates of the cost of adding a nitrification process to secondary waste treatment facilities and, thus, of increasing the percentage (P) of the total waste flow receiving nitrification.

It was necessary to select an interest, or discount, rate with which to amortize both the benefits of the hydroelectric peak generating capacity of Buford Dam and the capital cost of adding a nitrification process to the waste treatment facilities. If the peak generating capacity of Buford Dam is diminished by operating rules requiring releases from Lake Lanier for water-quality maintenance purposes, this capacity will have to be replaced (it is assumed) by an electric utility company in the private sector of the economy. The Georgia Power Company is currently constructing a hydroelectric pump-storage peaking facility (its "Rocky Mountain Project"), and is amortizing the capital cost of this facility using a discount rate of 11.24 percent (C.R. Thrasher, Georgia Power Company, written communication, June 5, 1978). Though the choice of a discount rate is somewhat subjective and requires a value judgement, a rate of 10 percent was chosen as being indicative of the opportunity cost of capital in the private sector of the economy.

All estimates of benefits and costs are presented in terms of first quarter, 1976, dollars.

Estimates of Benefits Given 1954-56 Drought Conditions

Recreation

Estimates of the benefits from recreation at Lake Lanier are based on data obtained from U.S. Army Corps of Engineer publications (U.S. Army Corps of Engineers, 1977).

According to the Corps of Engineers, the recreation benefits obtained from Lake Lanier vary with both the pool elevation of the reservoir and the season of the year. They have published estimates of both the peak and the off-peak season recreation benefits associated with pool elevation ranging from 1055 to 1080 feet above sea level. For example, the Corps of Engineers estimated that a pool elevation of 1070 feet has associated peak season benefits of $17,820,900 and off-peak season benefits of $13,011,100. For purposes of this study, it was assumed that the peak season benefits were distributed uniformly over the 22 weeks from May 1 through September 30 and that the off-peak season benefits were uniformly distributed over the 30 weeks from October 1 through April 30. Thus, a pool elevation of 1070 feet would have associated with it recreation benefits of $810,041/week during the peak season and $433,703/week during the off-peak season. The weekly recreation benefits associated with each pool elevation are depicted in figure 10.

The HSM provided the weekly pool elevation of Lake Lanier given that Buford Dam was to be operated so as to achieve a specified minimum flow at Atlanta. The weekly recreation benefits associated with each of the weekly

Figure 10.--Benefits from recreation on Lake Sydney Lanier given various pool elevations.

pool elevations were summed over the 132 weeks of the simulation period and averaged to obtain an estimate of the average annual recreation benefits from Lake Lanier (under 1954-56 drought conditions) given a specified minimum flow at Atlanta.

Hydroelectric Power and Peak Generating Capacity

To place a dollar value on the generating capacity of, and electric energy produced at, Buford Dam, it is necessary to ask: What is the least-cost method of producing an equivalent amount of electric energy by an alternative technique, and what is the cost? A detailed investigation of alternative techniques and their associated costs is beyond the scope of this study, but it is necessary to briefly discuss some of the details involved in such an investigation.

For purposes of analysis, it is useful to separate the cost of producing electric energy into two components: The capacity cost and the energy cost of production. The energy cost consists of the fuel (for example, coal) cost of producing a unit (for example, kWh) of electric energy. The capacity cost stems, primarily, from the capital investment in the generating facility. If an electric utility company is to invest in a generating facility, it must receive a rate of return on its investment at least equivalent to that which could have been earned if the money had been invested elsewhere; this is the so-called opportunity cost of capital, and it is determined by the interest or discount rate. The initial capital cost and useful life of a generating facility, along with the discount rate, are the main determinates of the capacity cost of producing electric energy at that facility.

As it is currently operated, Buford Dam is used primarily for generation of electric energy during periods of peak demand. Though it has been assumed herein that the Dam provides no <u>dependable</u> base generating capacity, it does produce some energy during non-peak hours because water is sometimes released during these hours to satisfy downstream flow requirements. Any non-peak energy produced at Buford Dam has an energy value equivalent to the cost of producing it by some least-cost alternative method. Similarly, the electric energy produced during peak periods has an energy value equivalent to the energy cost of producing it by some least-cost alternative.

To assign a capacity value to the generating capacity of Buford Dam and an energy value to the electric energy produced there, it is necessary to make an assumption as to the least-cost alternative source of capacity and energy. It was assumed that any peaking capacity lost at Buford Dam due to a change in its operating rules could be replaced by a facility similar in cost to the Georgia Power Company's 675 MW "Rocky Mountain" facility, which is scheduled to come on-line in 1983. Using data obtained from the Georgia Power Company (C.R. Thrasher, Georgia Power Company, written communication, June 5, 1978) and assuming a 10 percent discount rate, it is estimated that the capacity cost of electric energy produced by this pump-storage facility will be $23.34/kW/yr (in first quarter, 1976, dollars). The dependable peaking capacity of Buford Dam was assigned this value.

Electric energy produced at Buford Dam was assigned different values depending upon whether it was produced in a period of peak demand or in a period of base demand. According to estimates provided by the Atlanta Regional Office of the Federal Power Commission to the U.S. Army Corps of Engineers, (U.S. Army Corps of Engineers, 1977), the energy cost of electricity produced by coal-fired thermal electric power plants in the Atlanta area was 7.75 mills/kWh during the first quarter of 1976. Because any electricity produced at Buford Dam during periods of base demand could be substituted for electricity produced by coal-fired thermal electric plants, the base electricity produced at the Dam was assigned an energy value of 7.75 mills/kWh. However, if peak electricity produced at Buford Dam is to be replaced by electricity generated at a facility similar in cost to the Georgia Power Company's Rocky Mountain facility, such electricity must be assigned a higher energy value. The Georgia Power Company estimates that 1.4 kWh of electricity must be expended in pumping for storage (in off-peak periods) to generate 1.0 kWh of electricity in peak periods (Georgia Power Company, 1972). Given that base period electricity has an energy cost of 7.75 mills/kWh, then peak period electricity furnished by the Rocky Mountain pump-storage facility will have an energy cost of 10.85 mills/kWh (= 7.75 mills/kWh x 1.4). Accordingly, peak period electricity produced at Buford Dam was assigned an energy value of 10.85 mills/kWh.

It should be noted that the Corps of Engineers has assumed that the alternative to producing peak energy at Buford Dam is to produce it by a coal-fired thermal-electric power plant. Using estimates provided by the Atlanta Regional Office of the Federal Power Commission, the Corps of Engineers valued the dependable generating capacity of Buford Dam at $49.35/kW/yr. They assigned an energy value of 7.75 mills/kWh to electric energy produced at the Dam (U.S. Army Corps of Engineers, 1977). The sensitivity of the results of this study to the value assigned to dependable peak generating capacity is examined in a following section.

Given results of any run of the HSM, it is possible to compute the estimated annual energy benefits and dependable peaking capacity benefits (under the assumed drought conditions) associated with a particular Q_A. Energy benefits were calculated as the sum of average annual peak energy production multiplied by its value (10.85 mills/kWh) plus average annual non-peak energy production multiplied by its value (7.75 mills/kWh). Dependable peaking capacity benefits are equal to the dependable peaking capacity times its value ($23.34/kW/yr).

In table 7 is summarized the results of the HSM runs and the benefit calculations for the two cases (Q_A = 1290 ft^3/s and Q_A = 1600 ft^3/s) described in the previous section. Given 1990 water supply requirements and the drought conditions, the effects on annual benefits as a result of changing Q_A to 1600 ft^3/s from 1290 ft^3/s are: non-peak energy benefits increase by 30 percent, peak energy benefits decrease by 9 percent, dependable peaking capacity benefits decrease by 33 percent, and recreation benefits increase by 3 percent. Total benefits are decreased by one-half of one percent. In terms of benefits foregone, the cost of increasing Q_A to 1600 ft^3/s from 1290 ft^3/s in 1990 is estimated to be $150,000/yr.

Estimation of Average Annual Benefits

In the preceding section is described the method of estimating the benefits derived from Buford Dam under different operating rules given 1954-56 drought conditions. It is necessary to specify drought conditions to obtain an estimate of the maximum sustainable Q_A and of the dependable peaking capacity associated with each Q_A. It is not appropriate, however, to base an estimate of average annual benefits on worst-case (drought) conditions.

It would be more appropriate to base the estimates of the average annual benefits to be obtained under different minimum flows at Atlanta on a simulation of Dam operations over the entire available hydrologic record (including the worst-case drought). But, this would be an extended task. Also, it is only the change in average annual benefits (that is, benefits foregone) as a result of a change in Q_A that is of interest here. Thus, the estimates of the

Table 7.--HSM results and estimated benefits for 1990 given that the minimum flow at Atlanta is equal to (1) 1290 ft^3/s and (2) 1600 ft^3/s: 1954-56 drought conditions.

Minimum flow at the Atlanta gage in ft^3/s (Q_A)	1,290	1,600
Minimum flow at the confluence of the Chattahoochee River and Peachtree Creek in ft^3/s	1,180	1,490
Average annual non-peak energy (MWh/yr)	34,500	45,800
Average annual peak energy (MWh/yr)	98,000	88,600
Average annual energy (MWh/yr)	132,500	134,400
Dependable peaking capacity (MW)	98.1	65.9
Non-peak energy benefits ($ millions/yr)	.27	.35
Peak energy benefits ($ millions/yr)	1.06	.96
Dependable peaking capacity benefits ($ millions/yr)	2.29	1.54
Recreation benefits ($ millions/yr)	24.38	25.00
Total benefits ($ millions/yr)	28.00	27.85

benefits foregone associated with a change in Q_A were based on the simplifying assumption that the change in average annual benefits due to a change in Q_A is solely the result of the associated change in the dependable peaking capacity of Buford Dam.

From table 7, note that the sum of peak energy, non-peak energy, and recreation benefits increases with Q_A. Conversely, dependable peaking capacity benefits decrease with an increase in Q_A. This offsetting relationship does not hold for years of more nearly average or above average flows.

In any year, base and peak energy benefits and recreation benefits are a function of both the flows in that year and Q_A. But, dependable peaking capacity benefits are a function only of Q_A since they are determined only on the basis of the limiting (1954-56) hydrologic conditions. When water is more plentiful, setting Q_A at a high value (1600 ft^3/s) rather than a low value (1290 ft^3/s) does not have much effect on reservior operations or benefits. With plentiful water, it becomes possible to simultaneously satisfy the objectives of maximizing peak energy production, holding lake levels stable (near 1070 ft) for recreation, and providing high minimum flows at Atlanta.

As an example, consider the period from June 1959 through May 1960. During this period the average flow to Lake Lanier was 2229 ft^3/s, while June 1954 through May 1955 had an average flow of 1311 ft^3/s. After adjusting for storage, the reported (35-year) average flow at the U.S Geological Survey gage below Buford Dam is 2168 ft^3/s. Clearly, the period from June 1959 through May 1960 had more nearly average flows than did the years 1954-56.

The HSM was run using this 1959-60 record and the following constraints:

(1) All water-supply requirements (1990 levels) are satisfied.

(2) The release through the turbines during all peak power periods (52 weeks, 30 hours/week) is 10,000 ft^3/s.

(3) Reservoir storage is not to exceed 1.917 Maf (1070 ft).

The simulation was conducted for Q_A values of 1290 ft^3/s and 1600 ft^3/s.

The annual recreation benefits associated with the two minimum flows differ by less than $1000. The results of the simulation associate a minimum pool elevation of 1065.6 ft with a Q_A of 1290 ft^3/s and a minimum elevation of 1064.6 with a Q_A of 1600 ft^3/s. As can be seen in figure 10, recreation benefits are nearly the same for all elevations between 1064 and 1071 ft.

Peak energy production is nearly the same given a Q_A of either 1290 ft^3/s or 1600 ft^3/s. In both cases, there is a 10,000 ft^3/s flow through the power plant for 30 hrs/week during the full year at heads which differ by no more than 1 foot. As a result, the peak energy benefits associated with the two different values of Q_A differ by less than $2000.

Base energy production is also virtually the same for both values of Q_A. Whether Q_A is set at 1290 ft^3s or 1600 ft^3/s, the same total amount of water must be released during base power periods over the course of the year to keep the reservoir level from rising above 1070 ft. The heads being nearly the same, the difference in base energy benefits is very small.

Given the 1959-1960 flows, the only benefits significantly affected by the choice of Q_A are the dependable peaking capacity benefits. Given the 1959-60 hydrology, just as with the 1954-56 hydrology, an increase in Q_A to 1600 ft^3/s from 1290 ft^3/s decreases the dependable peaking capacity benefits by $0.75 million/yr (a 32,300 kW loss in capacity multiplied by the estimated capacity value of $23.34/kW/yr).

The sum of the changes in all three other types of benefits is a function of both Q_A and the hydrology of that particular year. As a result of an increase in Q_A to 1600 ft^3/s from 1290 ft^3/s the increase in the peak and non-peak energy benefits and the recreation benefits ranged from a total of

$0.56 million/yr under the most adverse hydrologic conditions to zero for average or above-average years.

Thus, the assumption that all benefits other than the dependable peaking capacity benefits are invariant with Q_A results in a slightly high estimate of the benefits foregone given an increase in Q_A. For simplicity, this assumption was adopted and the relationship between Q_A and average annual benefits foregone, as depicted in figure 11, was computed on this basis.

Estimation of Added Waste Treatment Costs

The location and flows of the waste treatment plants discharging wastes into the Chattahoochee River between Atlanta and Whitesburg were specified in table 1. These configurations, for each of the three years, are based on data obtained from the Atlanta Regional Commission.

In this study, the location and flows of the treatment plants are not considered to be decision variables; they are taken as given. Rather, the percentage (P) of the total waste flow receiving nitrification is considered to be the decision variable.

Data on waste treatment costs (Giffels, Black and Veatch, 1977) were used to develop estimates of the capital, operation, and maintenance costs of adding a nitrification process to secondary waste treatment plants. The capital costs were annualized using a 10 percent discount rate and then added to the annual operation and maintenance costs to obtain the estimated annual cost of adding the nitrification process to each treatment plant. These costs are presented in table 8. The costs of nitrification were estimated under the assumption that the required equipment would be operated year-around, though nitrification may not be required to maintain a given DO standard under some water-temperature conditions. Thus, the cost estimates presented in Table 8 may be biased upwards.

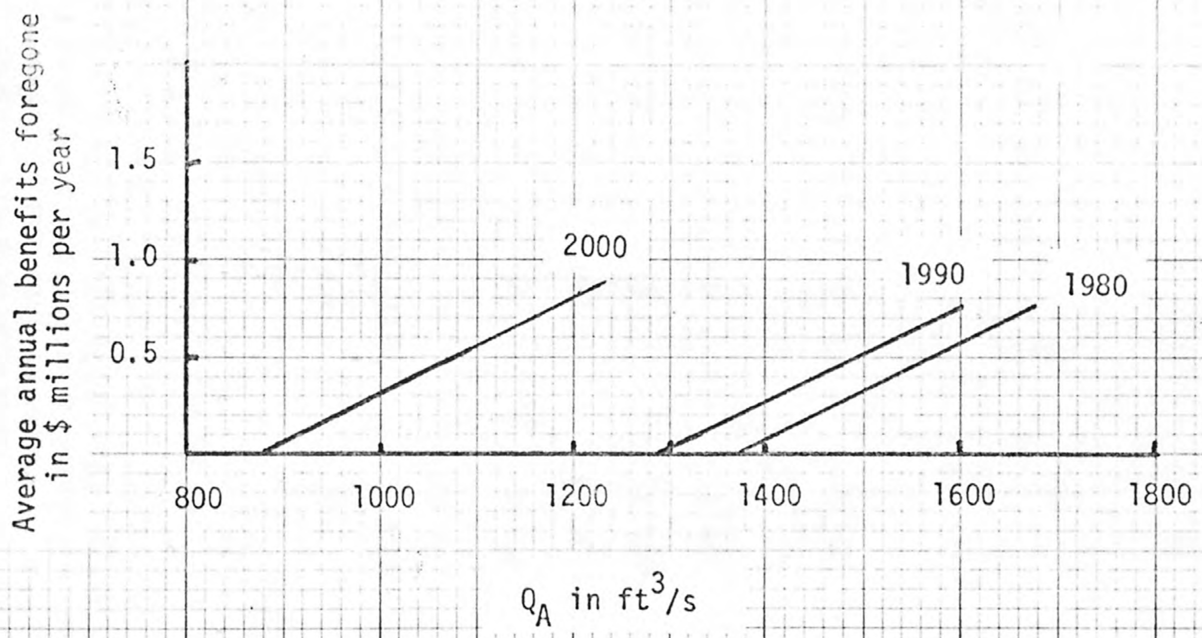


Figure 11.--The relationship between average annual benefits foregone and minimum flow at Atlanta (Q_A): 1980, 1990, and 2000.

Table 8.--The average daily flow of waste treatment plants discharging to the Chattahoochee River between Atlanta and Whitesburg, and the annualized cost of adding a nitrification process to the plants, (in 1st quarter, 1976 dollars).

Plant Name	River Mile	1980		1990		2000	
		Average flow (ft^3/s)	Annual cost ($1000)	Average flow (ft^3/s)	Annual cost ($1000)	Average flow (ft^3/s)	Annual cost ($1000)
Cobb-Chattahoochee	300.56	24	458.40	29	518.27	31	538.85
R. M. Clayton	300.24	131	1704.19	150	1932.45	161	2069.03
South Cobb	294.78	38	694.43	51	851.60	48	819.79
Utoy Creek	291.60	42	722.43	46	771.07	44	746.75
Sweetwater Creek	288.57	—	—	3	147.69	3	143.95
Camp Creek	283.78	15	359.82	22	444.02	27	507.63
Annewakee Creek	281.46	—	—	6	193.84	6	193.84
Regional Interceptor	281.45	—	—	—	—	42	726.14
Bear Creek	274.48	—	—	7	207.34	8	216.69

The data presented in table 8 were then used to develop estimates of the minimum annual cost of submitting any given percentage (P) of the total waste flow to nitrification. This was accomplished by identifying that plant or combination of plants which could provide nitrification for a given percentage of the total waste flow at a minimum cost. The total annual nitrification cost of this plant or combination of plants was then plotted against the percentage of the wastes receiving nitrification in 1980, 1990, and 2000 to obtain the cost curves depicted in figure 12. These cost curves are, of course, predicated on the particular treatment plants listed in tables 1 and 8.

At this point, it seems desirable to summarize what has been so far accomplished herein. A dissolved oxygen model was used to derive iso-DO curves which delineate the combinations of P and Q_A potentially capable of producing a given level of DO. A hydrologic simulation model was used to delimit the feasible values of Q_A and to provide a basis for estimating the costs (benefits foregone) associated with any given Q_A. Estimates of the benefits foregone as a result of an increase in Q_A and of the costs of increasing P have been developed. Given this information, it is now possible to identify the least-cost combination of P and Q_A capable of producing a given level of DO.

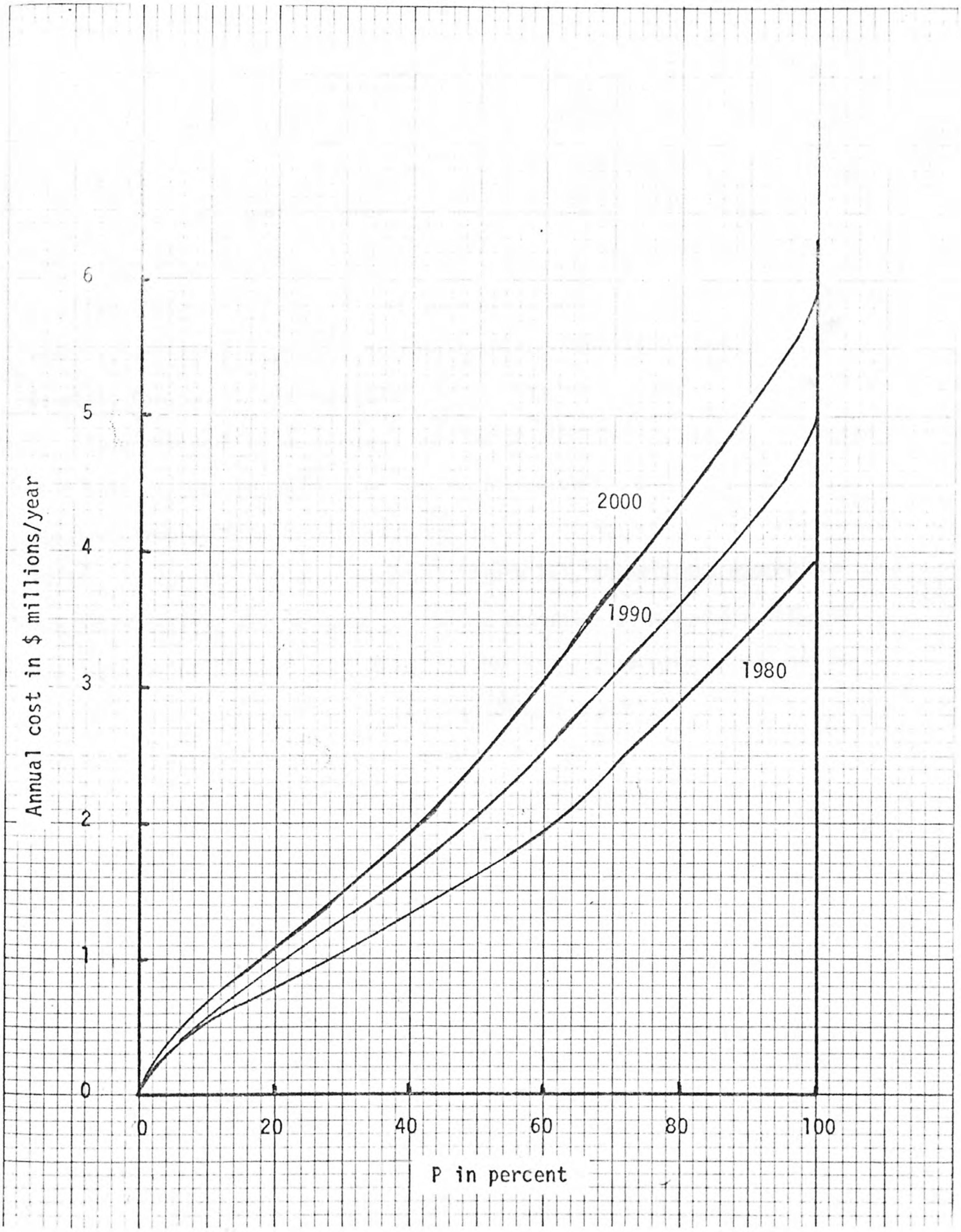


Figure 12.--The estimated annual cost of adding a nitrification process to secondary waste treatment plants as a function of the percentage (P) of the total waste flow receiving nitrification.

The Reregulation Project

The U.S. Army Corps of Engineers has considered a project involving construction of a reregulation structure on the Chattahoochee River just below Buford Dam along with dredging of the reservoir behind Morgan Falls Dam. This project would permit a more steady (and higher minimum) flow at Atlanta given any level of peak generating capacity at Buford Dam. Conversely, an increase in Q_A would result in less dependable peaking capacity benefits foregone if the reregulation structure were built.

In appendix A is described a version of the HSM in which it is assumed that this project is completed. The estimated costs of the project were obtained from a Corps of Engineers publication (U.S. Army Corps of Engineers, 1977). As is illustrated in appendix figure A-1, these costs exceed the project benefits, whether peak generating capacity is assigned a value of \$23.34/kW/yr or \$49.35/kW/yr. Thus, the reregulation project would not be included in a least-cost scheme for providing a given level of DO and received no further consideration herein.

Least-Cost Method of Producing a Given Minimum DO Concentration

It is useful to consider the problem at hand as one of finding the least-cost method of producing some given minimum DO concentration using two variable inputs: (1) some minimum flow rate at Atlanta (Q_A) and (2) some percentage (P) of the total waste load receiving nitrification in addition to secondary treatment. The curves labeled D = 3, D = 4, and D = 5 in figure 6, for example, give the various combinations of P and Q_A which are potentially capable of producing the indicated minimum DO concentration in 1990. If it is desired to "produce" a minimum DO concentration of, say, 4 mg/L in 1990, it only remains to find that feasible point (combination of P and Q_A) on the iso-DO curve labeled D = 4 in figure 6 that has associated with it a lower total cost in terms of benefits foregone and treatment costs than does any other feasible point on the curve.

Given the assumptions embedded in the HSM, the upper limit on the minimum flow that it is feasible to sustain at Atlanta is 1670 ft^3/s, 1600 ft^3/s, and 1230 ft^3/s in 1980, 1990, and 2000, respectively. Note that, from figure 6, it is feasible to attain a minimum DO concentration of 3 mg/L in 1990 without nitrification (P = 0) given a limit of 1600 ft^3/s on Q_A, as the maximum necessary Q_A is only 1430 ft^3/s. However, a minimum DO concentration of 4 mg/L requires, if P = 0, a minimum flow of about 1750 ft^3/s, whereas the maximum sustainable Q_A is only 1600 ft^3/s in 1990. If the minimum flow is set at the maximum sustainable in 1990, the upper end of the feasible range of the iso-DO curve for 4 mg/L requires that 24 percent of the total waste load receive nitrification (P = 24). The upper limit of the feasible range of an iso-DO curve is set by the lesser of either (1) the maximum necessary Q_A or (2) the maximum sustainable Q_A.

Every point on an iso-DO curve represents some combination of P and Q_A; thus each such point has an associated total cost. That cost can be determined using the output of the HSM and the estimated cost of nitrification and of dependable peak generating capacity. Consider, for example, point A in figure 6; here, P = 53 and Q_A = 1290 ft^3/s. From figure 11, it can be seen that, given this Q_A, there are no benefits foregone in 1990. From figure 12, it can be seen that the additional waste treatment costs associated with this P are equal to about 2.13 million dollars per year. Thus, point A (P = 53, Q_A = 1290 ft^3/s) has associated with it a total cost of 2.13 million dollars per year. Next consider point B in figure 6: P = 24 and Q_A = 1600 ft^3/s. From figure 11, it can be seen that at a Q_A of 1600 ft^3/s the benefits foregone equal 0.75 million dollars in 1990. The additional waste treatment costs incurred given that 24 percent of the total wastes are to receive nitrification equal 1.08 million dollars per year. Thus, the total cost associated with point B is 1.83 million dollars per year.

By calculating the total cost associated with each point on the iso-DO curves depicted in figure 6, it is possible to find that combination of P and Q_A that will "produce" a given minimum DO concentration at least-cost. It was determined that, for 1990, the least-cost method of attaining a minimum DO concentration of 4 mg/L is associated with point B in figure 6.

It can be more readily seen that point B does represent a (1990) least-cost combination of P and Q_A by inspecting figure 13. The curve labeled D = 4 in figure 13 corresponds to the similarly labeled iso-DO curve in figure 6.

The "kinked" curves in figure 13 connect combinations of P and Q_A which are associated with equal total costs; these curves are known as iso-cost curves. It has already been determined that point B in figure 13 (and the same point in figure 6) has an associated total cost of 1.83 million dollars

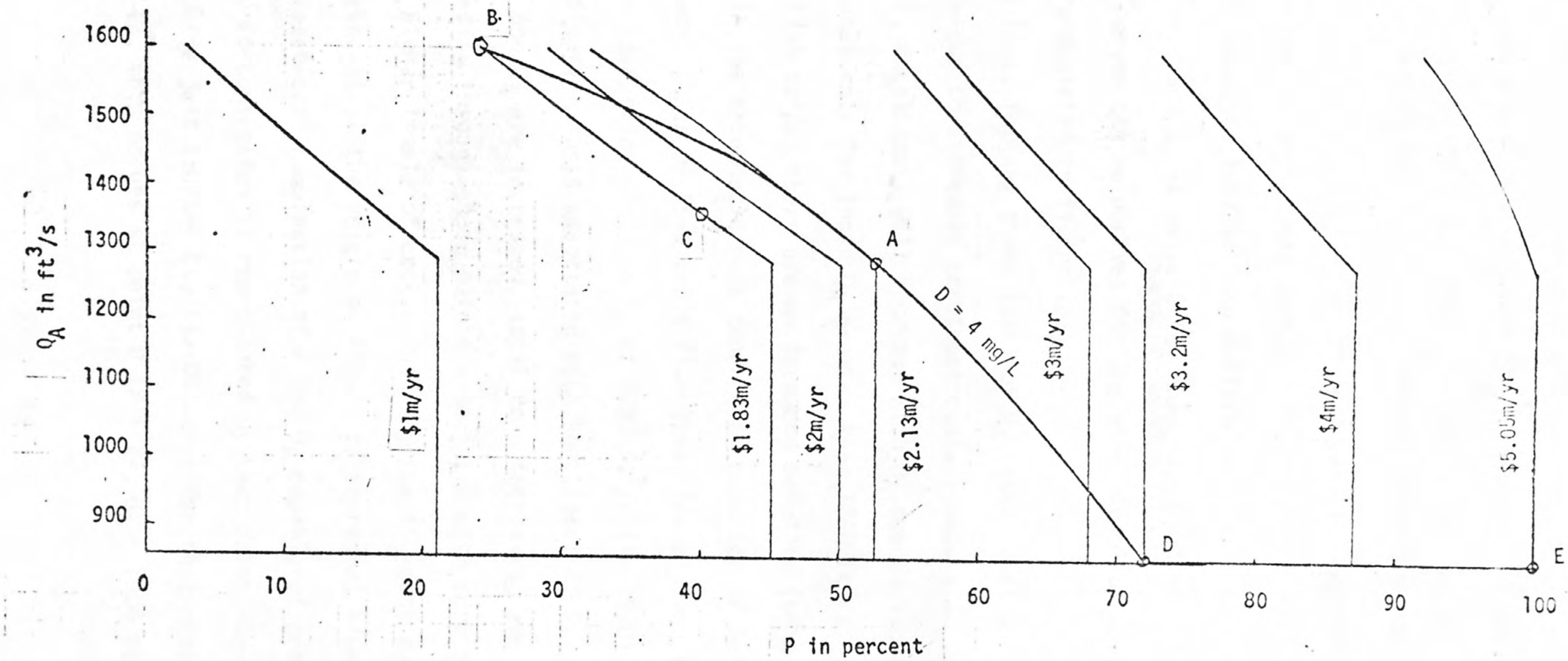


Figure 13.--An illustration of the method of determining the least-cost combinations of P and Q_A for producing a minimum DO concentration of 4 mg/L in 1990.

per year. Every combination of P and Q_A along the iso-cost curve which passes through point B has an associated total cost of 1.83 million dollars per year. For example, at point C (P = 40, Q_A = 1360 ft^3/s) on this iso-cost curve, the peak generating capacity benefits foregone given a Q_A of 1360 ft3/s are (from figure 11) 0.16 million dollars per year, and the additional treatment cost given that 40 percent of the wastes are to receive nitrification is (from figure 12) equal to 1.67 million dollars per year; the total cost of the combination of P and Q_A at point C is, then, 1.83 million dollars per year. Iso-cost curves can be derived for any given level of cost, and eight such curves are depicted in figure 13.

Note that, for any given level of Q_A, total cost will increase as P is increased--due to increased treatment costs. Note also that, for any given level of P, total costs will increase with Q_A due to increased benefits foregone--but only for those Q_A greater than 1290 ft^3/s (in 1990). For those Q_A below 1290 ft^3/s, there are no foregone benefits (that is, there is no decrease in the dependable peak generating capacity of Buford Dam) associated with an increase in Q_A (see table 6). Thus, for a given level of P, the iso-cost curve is vertical below a Q_A of 1290 ft^3/s (in 1990) and represents only the nitrification costs associated with that level of P. Finally, note that as <u>both</u> P and Q_A are increased, total cost increases, and thus the iso-cost curves passing through those points associated with more of both P and Q_A represent higher levels of cost. That is, the iso-cost curves lying farther to the northeast of the origin of figure 13 represent higher levels of cost.

The least-cost combination of P and Q_A capable of producing a given minimum DO concentration is represented by that point where the lowest possible iso-cost curve just touches the iso-DO curve for that minimum DO concentration; in figure 13, this occurs at point B (P = 24, Q_A = 1600 ft^3/s). All other combinations of P and Q_A capable of producing a minimum DO concentration of 4 mg/L in 1990 are associated with higher total costs.

The same procedure as that depicted in figure 13 was used to determine the least-cost method of producing a minimum DO concentration of both 3 mg/L and 5 mg/L in 1990. The results are presented in table 9 along with the least-cost combinations of producing the three minimum DO concentrations in 1980 and 2000. In table 9 are also presented the separate components of total cost: benefits foregone and the cost of adding the nitrification process to the waste treatment plants.

Note that, in comparing the least-cost combinations of a given DO standard across years, the DO standard of 5 mg/L provides the only case examined where the combination switches from no dependable peak generating capacity benefits foregone in 1980 to maximum sustainable flow in 1990 and then back to no benefits foregone in 2000. Comparing the least-cost combinations for all other DO standards across time reveals that they require the minimum flow at Atlanta be set at either the maximum necessary or maximum sustainable in 1980 and 1990 and then be reduced to 870 ft^3/s in 2000.

The solution for the least-cost combinations required to achieve a minimum DO concentration of 5 mg/L in 1980, 1990, and 2000 are depicted in figure 14. Note that the least-cost solution for 1990 would occur at that combination of P and Q_A represented by the point at the "kink" in the iso-cost curve if the slope of the upper portion of the iso-cost curve were only slightly "flatter." That is, the least-cost combination of P and Q_A given a DO standard of 5 mg/L nearly requires that Buford Dam be operated so as to forego no benefits from dependable peak generating capacity in 1990, just as it does require that it be so operated in 1980 and 2000.

Table 9.--Combinations of P and Q_A that will provide minimum DO concentrations of 3, 4, and 5 mg/L at least-cost: 1980, 1990, and 2000.

Minimum DO	Percent of wastes receiving nitrification (P)	Minimum flow at Atlanta (Q_A)	Cost of nitrification	Benefits foregone	Total cost
(mg/L)	(%)	(ft^3/s)	($M/yr)	($M/yr)	($M/yr)
		---1980---			
3	0	1380	0.00	0.00	0.00
4	0	1670	0.00	0.71	0.71
5	62	1380	2.03	0.00	2.03
		---1990---			
3	0	1430	0.00	0.34	0.34
4	24	1600	1.08	0.75	1.83
5	63	1600	2.72	0.75	3.47
		---2000---			
3	52	870	2.58	0.00	2.58
4	70	870	3.76	0.00	3.76
5	90	870	5.10	0.00	5.10

This suggests two (related) questions:

1. How sensitive is the least-cost solution to the value of the parameters that determine the slope of the iso-cost curves?

2. How much difference would it make, in terms of added cost, if the least-cost solution were not chosen?

It is to these questions that we now turn.

Sensitivity of the Least-Cost Solution to the Cost of Dependable Peak Generating Capacity

Given the shapes of the iso-cost and iso-DO curves derived in this study, the least-cost combination of P and Q_A is found at either the upper end of the feasible range of the iso-DO curve or where the "kink" in an iso-cost curve just touches the iso-DO Curve. That is, the least-cost combination will require that Buford Dam either be operated so as to maintain the minimum flow at Atlanta at the maximum (necessary or sustainable) or that it be operated so as to forego no benefits from dependable peak generating capacity.

An increase in the cost of dependable peak generating capacity relative to that of nitrification would be sufficient to decrease the slope of the iso-cost curves. Any given level of total cost will be attained at a lower Q_A after an increase in the cost of peak generating capacity because the benefits foregone due to the loss of such capacity will be greater at each Q_A which would cause such a loss. However, given some positive cost for dependable peak generating capacity, that Q_A below which no capacity benefits are foregone will remain the same. Thus, the iso-cost curves associated with higher costs of peak generating capacity will lie below and have a lesser slope than will such curves associated with lower capacity costs.

Given a sufficient increase in the cost of peak generating capacity relative to that of nitrification, the least-cost combinations of attaining any given minimum DO concentration will switch from those requiring a maximum (necessary or sustainable) minimum flow at Atlanta to those that require that no dependable peak generating capacity benefits be foregone at Buford Dam. The dependable peak generating capacity costs which cause such a switch in the least-cost combination of P and Q_A are presented in table 10.

We have assumed that the replacement cost of dependable peak generating capacity at Buford Dam is equal to the \$23.34/kW/yr estimated cost of the "Rocky Mountain" hydropower pump-storage facility. Consequently, the least-cost combination requires that there be no dependable peak generating capacity foregone to provide a minimum DO concentration of either 3, 4, or 5 mg/L in 2000 and to provide a mimimum DO concentration of 5 mg/L in 1980. But, note that our estimate of \$23.34/kW/yr is close to those costs which would require that no peak generating capacity be foregone to provide a minimum DO concentration of either 3 or 4 mg/L in 2000 and to provide a minimum DO concentration of 5 mg/L in 1990. For these DO standards in these years, the least-cost combination of P and Q_A is quite sensitive to the estimate of the cost of dependable peak generating capacity.

As was previously noted, the U.S. Army Corps of Engineers has assumed that any loss of dependable peak generating capacity at Buford Dam would be replaced using thermal electric generating facilities at a cost of \$49.35/kW/yr. Using such a replacement cost, the least-cost combination of P and Q_A requires that Buford Dam be operated so as to forego no benefits from dependable peak generating capacity in providing a minimum DO concentration of either 4 or 5 mg/L. The least-cost combination would require that the Dam be operated so as to maintain the maximum necessary Q_A in 1980 and the maximum sustainable Q_A

Table 10.--Costs of dependable peak generating capacity above which the indicated minimum DO can be achieved at least-cost by operating Buford Dam so as to forego no benefits from dependable peak generating capacity. (First quarter, 1976 dollars.)

Minimum DO mg/L	Year 1980 $/kW/yr	1990 $/kW/yr	2000 $/kW/yr
3	(a)	69	21
4	34	33	22
5	17	25	16

(a) Not necessary to forego peak generating capacity even if Q_A set at the maximum necessary (1380 ft^3/s) to achieve a minimum DO of 3 mg/l.

in 1990 if the DO standard were set at 3 mg/L. But, no peak generating capacity would be foregone in 1980 given that the maximum Q_A necessary to maintain a minimum DO concentration of 3 mg/L is only 1380 ft^3/s.

Suppose that the replacement cost of the dependable peak generating capacity of Buford Dam is $49.35/kW/yr, but that the choice of the least-cost combination of P and Q_A is based on an estimated cost of $23.34/kW/yr. Conversely, suppose that the replacement cost is really $23.34/kW/yr, but that the least-cost combination is chosen under the assumption that the replacement cost is $49.35/kW/yr. In each case, the actual total cost will be greater than the calculated total cost of that which is (mistakenly) thought to be the least-cost combination of P and Q_A. The difference between the actual and calculated total costs is a measure of the loss in economic efficiency which would result from the use of an erroneous estimate of the cost of peak generating capacity.

In table 11 are presented the economic efficiency losses which would result if the cost of peak generating capacity were actually $49.35/kW/yr but if the least-cost combination were calculated and selected using an estimated cost of $23.34/kW/yr. Also presented is the correct least-cost combination of P and Q_A if the cost is actually $49.35/kW/yr. If the minimum DO concentration were set at 5 mg/L in 1990, for example, the calculated least-cost combination would require that 63 percent of the total wastes receive nitrification and that the minimum flow at Atlanta be set at 1600 ft^3/s. But, the correct least-cost combination would require that 78 percent of the waste receive nitrification and the minimum flow at Atlanta be set at 1290 ft^3/s. If we have underestimated the cost of peak generating capacity by $26.01/kW/yr (=$49.35 - $23.34), our (erroneous) least-cost combination of P and Q_A results in a $800,000/yr efficiency loss given a 5 mg/L DO standard in 1990. This

Table 11.--Efficiency loss if least-cost combination of P and Q_A is selected under the assumption that the cost of peak generating capacity is $23.34/kW/yr but actual cost is $49.35/kW/yr.

Min DO	Calculated least-cost combination		Correct least-cost combination		Economic efficiency loss
	P	Q_A	P	Q_A	
(mg/L)	(%)	(ft^3/s)	(%)	(ft^3/s)	($M/yr)
			---1980---		
3	0	1380	0	1380	0.00
4	0	1670	31	1380	0.37
5	62	1380	62	1380	0.00
			---1990---		
3	0	1430	0	1430	0.00
4	24	1600	52	1290	0.54
5	63	1600	78	1290	0.80
			---2000---		
3	52	870	52	870	0.00
4	70	870	70	870	0.00
5	90	870	90	870	0.00

efficiency loss would result from too little nitrification and too much peak generating capacity lost relative to the "correct" least-cost combination.

In table 12 are presented the efficiency losses which would result if the cost of peak generating capacity were actually \$23.34/kW/yr but if the least-cost combination were calculated and selected using an estimated cost of \$49.35/kW/yr. In this case, if the minimum DO concentration were set at 5 mg/L for 1990, the calculated least-cost combination would require that 78 percent of the wastes receive nitrification and that the minimum flow at Atlanta be set at 1290 ft^3/s. But, the correct least-cost combination would require that only 63 percent of the waste receive nitrification and that the minimum flow at Atlanta be set at 1600 ft^3/s. If the cost of peak generating capacity is overestimated by \$26.01, the (erroneous) least-cost combination of P and Q_A results in a \$40,000/yr efficiency loss in 1990 given a 5 mg/L DO standard.

Note that, given the two estimates of peak generating capacity cost, there are only three cases in which there is an economic efficiency loss associated with the choice of one estimate of the cost over the other: for a DO standard of 4 mg/L in 1980 and 1990 and for a standard of 5 mg/L in 1990. Note also that the "switching costs" presented in table 10 fall between \$23.34/kW/yr and \$49.35/kW/yr only in these three cases. For all other cases, the least-cost combination of P and Q_A is the same given a peak generating capacity cost of either \$23.34/kW/yr or \$49.35/kW/yr.

If a decision maker is uncertain as to the cost of peak generating capacity and is risk adverse, he might prefer to minimize the maximum possible economic efficiency loss by choosing to base the selection of the least-cost combination on an estimated capacity of \$49.35/kW/yr. However, we believe that it is inappropriate to assume that any peak generating capacity lost at Buford Dam

Table 12.--Economic efficiency loss if least-cost combination of P and Q_A is selected under the assumption that the cost of peak generating capacity is \$49.35/kW/yr but actual cost is \$23.34/kW/yr.

	Calculated least-cost combination		Correct least-cost combination		Economic efficiency loss
Min DO	P	Q_A	P	Q_A	
(mg/L)	(%)	(ft^3/s)	(%)	(ft^3/s)	(\$M/yr)
---1980--					
3	0	1380	0	1380	0.00
4	31	1380	0	1670	0.42
5	62	1380	62	1380	0.00
---1990---					
3	0	1430	0	1430	0.00
4	52	1290	24	1600	0.30
5	78	1290	63	1600	0.04
---2000---					
3	52	870	52	870	0.00
4	70	870	70	870	0.00
5	90	870	90	870	0.00

would be replaced by thermal electric facilities. We prefer to base our calculations on the assumption that the peak generating capacity would be replaced by a facility similar in cost to the "Rocky Mountain" hydropower pump-storage facility. It is apparent that the Georgia Power Company found hydropower pump-storage to be the least-cost method of obtaining additional peak generating capacity.

Institutional Constraints and Associated Costs

The least-cost combinations of P and Q_A which are presented in table 9 are based on the assumption that there is complete flexibility in the choice of P and Q_A. In reality, there may exist constraints, in the form of laws or regulations, that restrict the range of choice of P and/or Q_A. The question then becomes: What is the least-cost plan given these constraints, and what is the cost of that plan?

Currently, the Georgia Department of Natural Resources requires that a minimum flow of 750 ft^3/s be maintained in the Chattahoochee River immediately upstream of the confluence of Peachtree Creek (U.S. Army Corps of Engineers, 1977). This translates to a minimum flow requirement of 860 ft^3/s at the Atlanta gage.

If this requirement sets the Q_A at 860 ft^3/s, and no higher, then the problem of finding the "least-cost" method of producing a given minimum DO concentration is reduced to simply finding the minimum level of nitrification (that is, the minimum P) that will provide that DO concentration given this constraint on Q_A. For example, given a DO standard of 4 mg/L in 1990 and a Q_A of 860 ft^3/s, the least-cost combination is given by point D in figure 13. Given the constraint on Q_A, 72 percent of the total waste must receive nitrification if a minimum DO of 4 mg/L is to be attained. The cost associated with this (constrained) least-cost combination is given by the iso-cost curve which passes through point D in figure 13: 3.2 million dollars/yr. The same procedure was used to find the least-cost method of providing a minimum DO concentration of both 3 mg/L and 5 mg/L in 1990 given a Q_A of 860 ft^3/s. The results are presented in table 13 and, graphically, in figure 15. (Points D and B in figure 15 correspond to the similarly labeled points in figure 13.)

Table 13.--Percentage of wastes that must receive nitrification to provide minimum DO concentration at 3, 4, and 5 mg/L at least-cost given that the minimum flow at Atlanta is constrained to 860 ft^3/s: 1980, 1990, and 2000.

Minimum DO	Percent of waste receiving nitrification (P)	Minimum flow at Atlanta (Q_A)	Cost of nitrification	Benefits foregone	Total cost
(mg/L)	(%)	(ft^3/s)	($M/yr)	($M/yr)	($M/yr)
		---1980---			
3	39	860	1.35	0.00	1.35
4	59	860	1.91	0.00	1.91
5	84	860	3.12	0.00	3.12
		---1990---			
3	52	860	2.10	0.00	2.10
4	72	860	3.20	0.00	3.20
5	92	860	4.30	0.00	4.30
		---2000---			
3	52	860	2.58	0.00	2.58
4	70	860	3.76	0.00	3.76
5	90	860	5.10	0.00	5.10

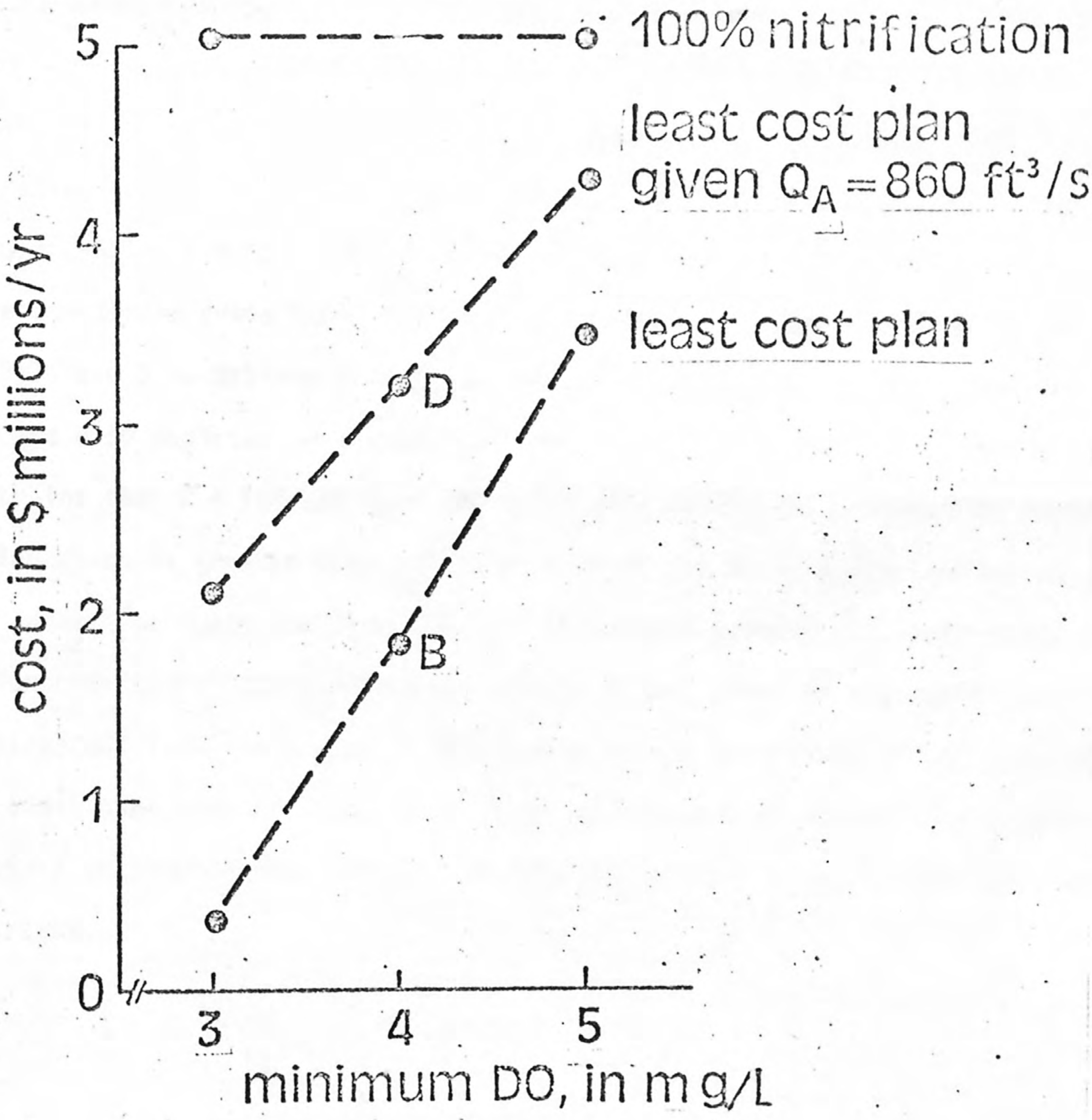


Figure 15.--Cost (benefits foregone plus added waste treatment cost) of attaining various minimum DO concentrations under different policies: 1990. Note that cost is independent of the DO standard given a constraint of 100% nitrification.

The least cost-cost methods of producing minimum DO concentrations of 3 and 5 mg/L in 1980 and 2000, given that Q_A is constrained to 860 ft^3/s, are also described in table 13.

As another example of a constraint and its associated cost, suppose that there existed a requirement that Q_A be set a 860 ft^3/s and that all wastes receive nitrification (P = 100). Because there are no dependable peak generating capacity benefits foregone under this plan, the total costs are those of adding a nitrification process to all secondary treatment plants; these annualized costs total 3.95 million dollars in 1980, 5.05 million dollars in 1990, and 5.95 million dollars in 2000. The total costs under this plan in 1990 are also depicted in figure 13. Note that, from figures 5 through 7, the constraint that P = 100 and Q_A = 860 ft^3/s will result in a minimum DO concentration which is greater than 5 mg/L in each of the three years considered.

In each of these two examples, the difference between the lower costs of the "unconstrained" least-cost plan and the higher costs of the corresponding "constrained" least-cost plan is due solely to the imposition of the constraint. This additional cost provides an estimate of the cost of obtaining any benefits (monetary or nonmonetary, tangible or intangible) that might result from the constraint.

Concluding Remarks

This study has placed a DO management problem in a conceptual framework suggested by the economic theory of production. The minimum flow of the Chattahoochee River and the percentage of the waste inflow receiving nitrification are considered to be two variable inputs that can be used to produce a given concentration of dissolved oxygen in the River. Results of the USGS Chattahoochee River Quality Assessment project were used to establish the production relationship between minimum flow, waste treatment, and DO concentration. Each of the inputs has a cost: the loss of dependable peaking capacity benefits associated with flow augmentation and the cost associated with nitrification of wastes. An attempt was made to find the least-cost combination of minimum flow and waste treatment to achieve a prescribed minimum DO concentration.

No attempt was made to identify the benefits associated with various concentrations of DO in the River. Thus, no attempt was made to provide an estimate of the minimum DO concentration which would maximize the net benefits from producing dissolved oxygen in the River.

It was not an objective of this study to prescribe a specific set of operating rules for Buford Dam and a waste treatment plan for the Atlanta Region. An objective was to demonstrate a method for evaluating the cost-effectiveness of alternative strategies for DO management; the method is the primary message. The Chattahoochee River was used as an example because of the availability of USGS data and models which could be used to derive the DO production relationship. Another objective was to demonstrate how the results of a USGS Intensive River Quality Assessment could be applied to a water-quality management problem.

The ISO-DO curves presented in figures 5 through 7 were derived using the DO model of the Chattahoochee River developed by Stamer and others (1978). These curves describe the physical relationship between flow augmentation, nitrification and DO, and are useful in themselves. When cast within an economic framework, they provide a basis for decision-making.

In regard to the Chattahoochee River, the results indicate that, for certain DO standards and between now and 2000, the waste assimilative capacity of increased flows in the Chattahoochee River can be substituted for increased waste treatment. It is estimated that the savings in waste treatment costs experienced by so doing will more than offset the benefits foregone due to the loss of peak generating capacity at Buford Dam. However, these results were demonstrated to be, in some cases, sensitive to the value assigned to peak generating capacity, and may also be sensitive to (among other things) estimates of the discount rate and the costs of nitrification.

There is a strong indication that a flexible approach to the management of DO in the Chattahoochee River may be much more cost-effective than a more rigid, institutional, approach. Examples of such rigid approaches are prohibitions of flow augmentation for water-quality management, or blanket requirements for high levels of waste treatment without regard to concomitant costs and resulting water-quality levels. An institutional constraint on flow augmentation or waste treatment practices will not, in general, be consistent with the attainment of a prescribed DO standard at least-cost. That is to say, such constraints will usually have an associated cost (or economic efficiency loss).

Finally, note that our criterion for evaluating different DO management strategies has been solely one of economic efficiency: What is the minimum-cost method of meeting a given DO standard? Equity, or distributional, considerations have been completely ignored. For example, to attain a minimum DO concentration of 5 mg/L in the Chattahoochee River in 1980 and 1990, the least-cost strategy requires that a little over 60 percent of the total waste flow receive nitrification and that, consequently, about 40 percent of the flow receive only secondary treatment. If the additional cost of nitrification is borne only by the taxpayers in the service area of those plants required to add the nitrification process, the taxpayers serviced by those plants at which nitrification is not required do not bear any of the additional waste treatment cost incurred in meeting the DO standard. As another example, consider that in choosing between combinations of P and Q_A that will produce a given level of DO, some combinations require that more dependable peaking capacity be foregone and less additional waste treatment costs be incurred than do others. Those individuals that bear the costs of replacing the peaking capacity and those that experience the savings in treatment costs because the peaking capacity has been foregone are not necessarily the same individuals. The choice of a lease-cost method for attaining a given minimum DO concentration has distributional or equity implications which have not been considered in this study.

Appendix A
Analysis of the Reregulation Project

If the proposed reregulation structure were built just below Buford Dam (capacity 8400 acre-feet) and Morgan Falls reservoir were dredged to a capacity of 3500 acre-feet, then it would be possible to produce more peak hydroelectric power for a given required minimum flow at the Atlanta gage. By storing more of the water released from Buford Dam during peaking hours, it becomes possible to meet most or all of the water supply and minimum flow needs throughout the entire week.

The HSM was modified to simulate this situation, two variables were added to account for the addition of the reregulating structure: S_R (storage in ft^3) and Q_R (discharge from the reregulating structure in ft^3/s). The additional flow and storage constraints of the HSM are these:

$$\frac{dS_R}{dt} = Q_1 - Q_R \qquad (12)$$

$$S_R(t_o) = 0 \qquad (13)$$

$$S_R(t_f) \geq 0 \qquad (14)$$

$$S_R \leq 3.66 \times 10^8 \qquad (15)$$

Some other constraints in the original HSM are changed as follows:

$$Q_R + T_2 \geq W_2 \qquad (6a)$$

$$\frac{dS_2}{dt} = Q_R + T_2 - W_2 - Q_2 \qquad (7a)$$

$$S_2 \leq 1.52 \times 10^8 \qquad (10a)$$

Explanation of added and changed constraints

(12) Continuity equation for the reregulating reservoir

(13) & (14) Initial and final storage in reregulating reservoir reservoir (arbitrary)

(15) Capacity constraint for reregulating reservoir $3.66 \times 10^8\ ft^3$ = 8400 acre feet

(6a) The withdrawals below Buford Dam but above Morgan Falls must be satisfied by the release from the regegulating reservoir plus tributary flows.

(7a) Continuity equation for Morgan Falls: The inflow is the release from the reregulating reservoir plus tributary flow minus withdrawals.

(10a) The capacity of Morgan Falls reservoir is increased by dredging to 1.52×10^8 ft^3 = 3,500 acre feet.

This modified HSM was run to determine the relationship between dependable peaking capacity and Q_A for each of the three years.

Figure A-1 shows the dependable peaking capacity benefits as a function of Q_A, with and without the reregulating structure and Morgan Falls dredging. Also show on this figure are these benefits minus the cost of these improvements.

According to the Corps of Engineers' Lake Lanier Restudy, the capital cost of the reregulating structure is $11.50 million and the operation and maintenance costs are $65,800/yr. Using a discount rate of 10 percent and a life of 100 years, the annualized cost of the facility is $1.22 million/yr. The Corps reports the initial cost of the Morgan Falls dredging is $1.65 million with annual maintenance dredging costs of $15,000/yr. Using a 10 percent discount rate and a 100 year life, the annualized cost of the Morgan Falls dredging is $0.18 million/yr. Thus, the annual cost of both projects is $1.40 million/yr.

The figures show that the costs of these improvements exceeds the gain in dependable peaking capacity benefits. These calculations were made under the assumption that the value of dependable peaking capacity is $23.34/kW/yr. Even if this value were assumed to be $49.35/kW/yr, the costs of the improvements would exceed the gain in dependable peaking capacity benefits. There may, however, be other benefits from the project such as enhancement of the river for recreational use, or the mitigation of channel erosion.

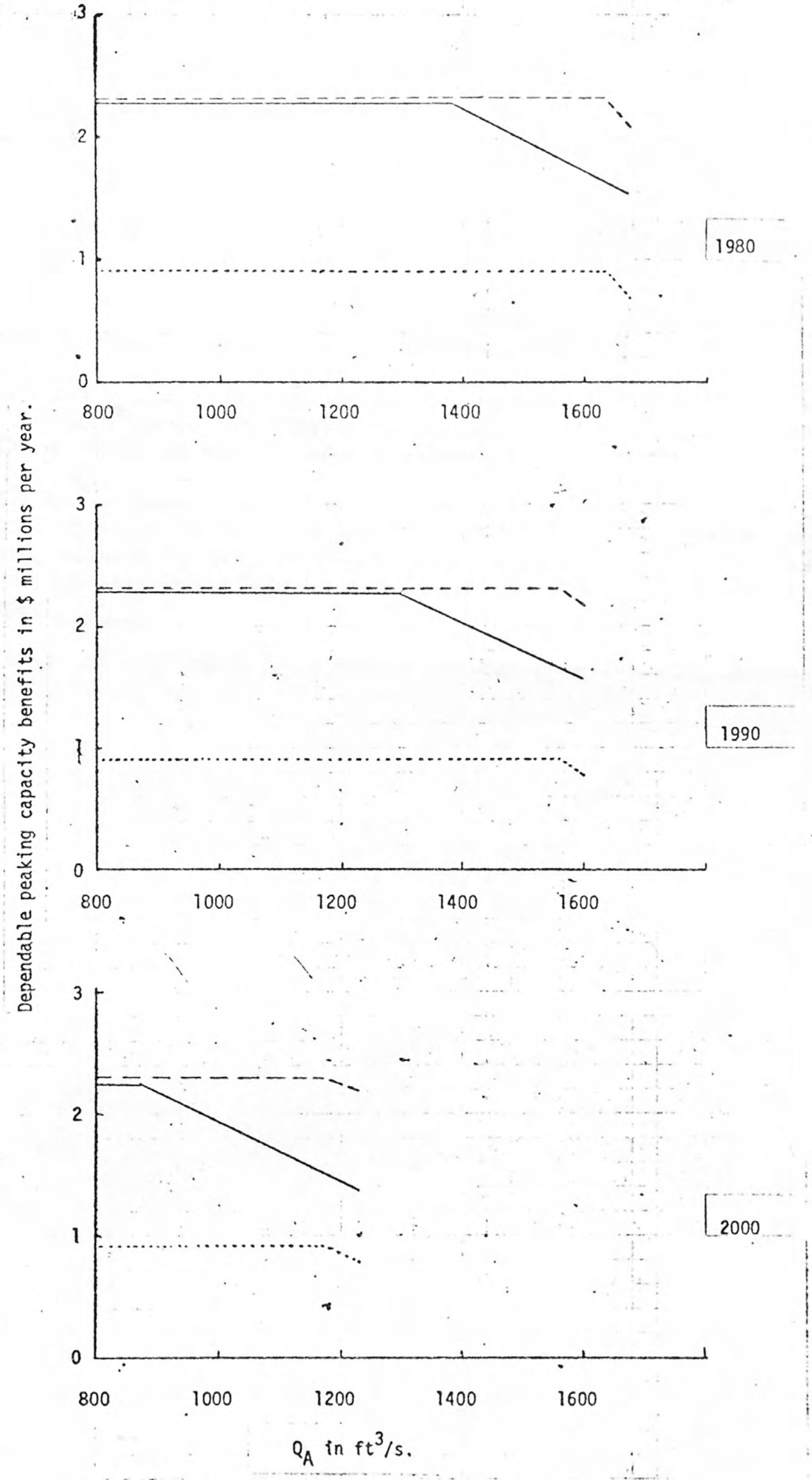


Figure A1.--The relationship between estimated annual dependable peaking capacity benefits and minimum flow at Atlanta (Q_A), with and without reregulation, 1980, 1990, and 2000. Solid line is without reregulation, dashed line is with reregulation, dotted line is benefits with reregulation minus the annualized cost of reregulation.

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