An Economic Analysis of Selected Strategies for Dissolved-Oxygen Management: Chattahoochee River, Georgia

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1140

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By JOHN E. SCHEFTER *and* ROBERT M. HIRSCH

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A method for evaluating the cost effectiveness of alternative strategies for dissolved-oxygen management is demonstrated

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By JOHN E. SCHEFTER and ROBERT M. HIRSCH

ABSTRACT

A method for evaluating the cost-effectiveness of alternative strategies for dissolved-oxygen (DO) management is demonstrated, using the Chattahoochee River, Ga., as an example. 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 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 necessary to achieve a prescribed minimum DO concentration is identified.

Results of the study indicate that, in some instances, the waste-assimilation capacity of the Chattahoochee River can be substituted for increased waste treatment; the associated savings in waste-treatment costs more than offset the benefits foregone because of 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) on 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 (U.S.G.S.) River Quality Assessment can be applied within the context of economic analysis to a DO management problem. Results of the U.S.G.S. 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, Ga., and West Point Lake, Ga.

NATURE OF THE PROBLEM

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

The occurrences of low DO concentrations correspond closely with the occurrences of low discharge of 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 traveltime upstream of Fairburn.

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 to this study are identified and located by river mile.

The multipurpose Buford Dam impounds Lake Sidney 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 Sidney Lanier project, the U.S. Army Corps of Engineers (1977) estimated that 74 percent of the average annual benefits come from recreation, 17 percent from hydroelectric power, and the remainder from flood control, navigation (in the Apalachicola waterway), water supply (for the Atlanta metropolitan area), and low-flow and water-quality maintenance (for the Chattahoochee River from Atlanta to West Point Lake).

Buford Dam has an installed hydroelectric generating capacity of 105 MW (megawatts), which is used primarily during periods of peak demand. Electricity is generated primarily about 6 hours per day on weekdays. During these peak hours water is released from Lake Sidney Lanier at a rate as high as 10,000 ft^3/s, and at

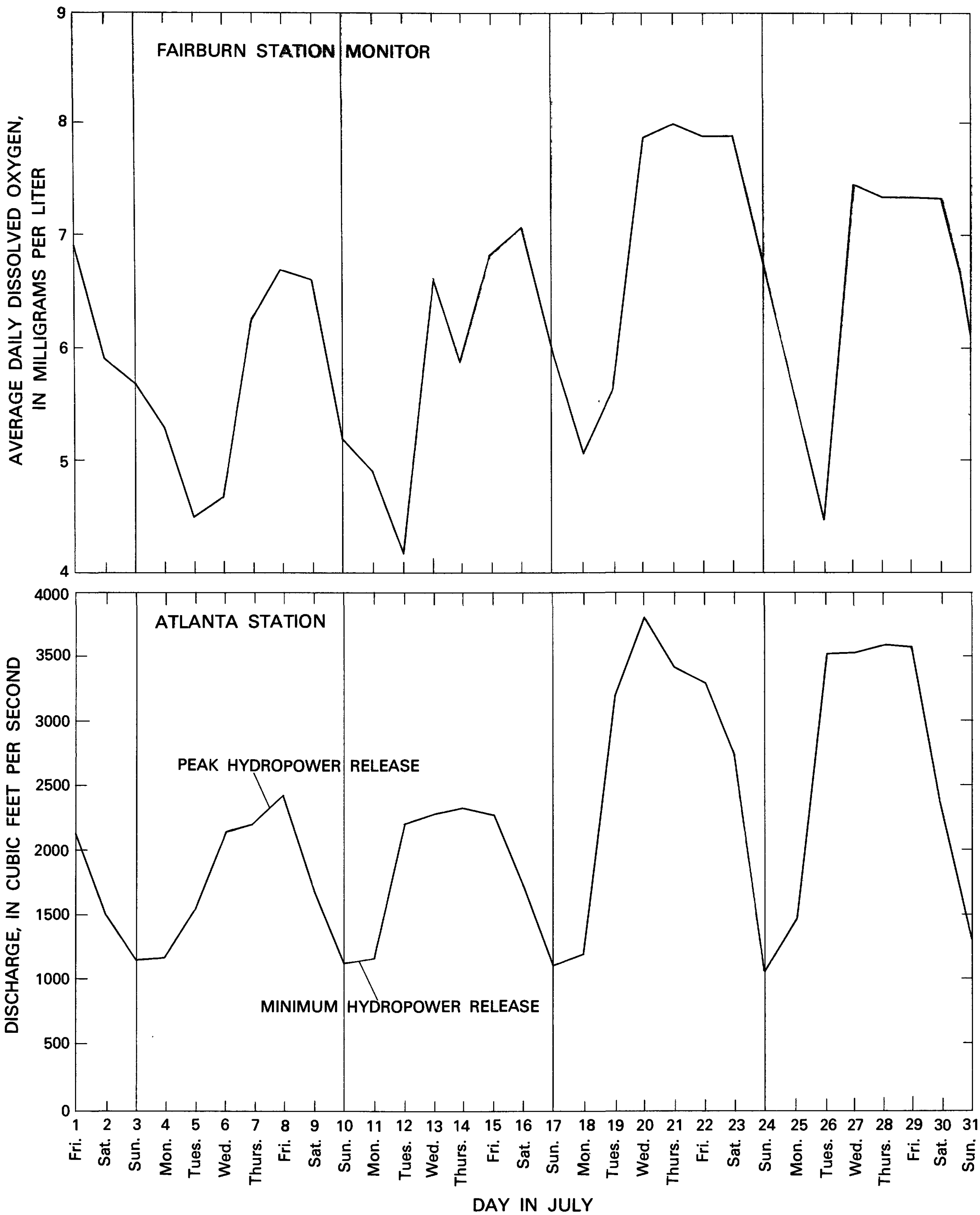

FIGURE 1. – Dissolved-oxygen concentrations at the Fairburn, Ga., station monitor and mean daily discharge at the Atlanta, Ga., station during July 1977.

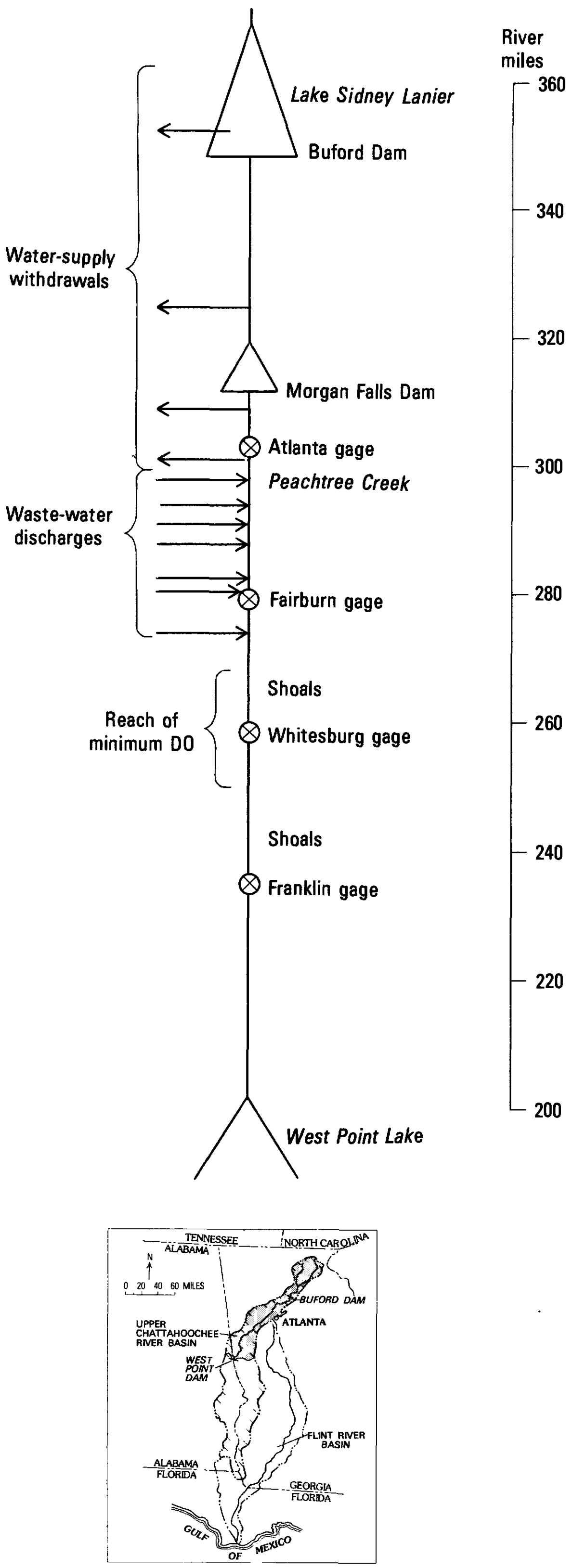

FIGURE 2.–Schematic map of the study reach of the Chattahoochee River, Ga. (DO, dissolved oxygen.)

other times (morning, lates 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 Buford Dam and Atlanta. There is some tributary inflow between Buford Dam and Atlanta, but there are also water-supply withdrawals in this reach. The effects of the low release rates at Buford Dam that occur from late Friday night through midday Monday are somewhat mitigated but are very evident in the Sunday and Monday flows at Atlanta.

RELATIONSHIP OF FLOW AND DISSOLVED OXYGEN

There are three mechanisms whereby increased 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 generally cause less exchange of oxygen from the air to the water per unit volume of water and result in a lower DO concentration throughout the sag. The third is the decrease in travel time to the shoals, which are located between 30 and 50 miles below Atlanta. 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 three mechanisms 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 DISSOLVED-OXYGEN CONCENTRATION

Stamer and others (1978) reported that on June 1–2, 1977, when the river flow at the Atlanta gage was 1,150 ft^3/s, the minimum DO in the river was 4.0 mg/L and the DO was less than 5.0 mg/L along approximately a 20 mile reach. At that time, the flow of waste water into the river was 185.3 ft^3/s. The average concentration of the ultimate biochemical oxygen demand (BOD_u) of the waste water 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 conditions anticipated for the year 2000 and with secondary waste treatment (370 ft^3/s of waste water, BOD_u concentrations 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 less than 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 1,800 ft^3/s instead of 1,150 ft^3/s in 2,000, the minimum DO concentration would be 2.6 mg/L, and a reach of 43 miles would have a DO concentration less than 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 were 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 1,150 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

A number of techniques can be conceived 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. Developing sources of water supply outside of the Chattahoochee River basin, so that more water could be available for water-quality maintenance.
5. Reducing the rates of water use (and, thus, sewage discharge), especially during low flow periods; this reduction could be accomplished by a number of rationing and (or) water-pricing schemes.
6. Dredging 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. Construction of a reregulation structure (dam and reservoir) between Buford Dam and Morgan Falls Dam so as to permit a more steady flow at Atlanta.
8. Changing 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):

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 that secondary treatment is used 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 Sidney Lanier for water-quality maintenance purposes.

Monetary costs are of course 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 Sidney Lanier that would affect recreation benefits and the amount of electrical energy produced per unit volume of water released. The relative proportion of high-valued peak power and lower-valued nonpeak (or base) power may change. Most importantly, as more water is reserved for low-flow maintenance less water is dependably available for peak power generation and the dependable peak generating (peaking) capacity of the generators at Buford Dam may change. 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 change in the operation of Buford Dam for purposes of maintaining water quality 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 three techniques (nitrification, change in the operation of Buford Dam for water-quality maintenance, and improved reregulation) 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-concentration 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 to the river will increase along 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 of Lake Sidney 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 costs are incurred in achieving or maintaining a given level of water quality in the Chattahoochee River, benefits may also be gained from so doing. Economic-efficiency criteria state that the net benefits to be obtained from an increase in the DO concentration of a 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 that will maximize net benefits.

STUDY OVERVIEW

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

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

The methods used to obtain estimates of the change in hydroelectric power and recreation benefits and of the waste-treatment costs are next 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 Sidney Lanier and Chattahoochee River waters for enhancement of its DO concentration on the one hand and hydroelectric-power generation on the other. That is, we asked to what extent can the waste-assimilation 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 at river mile (rm) 302.97 to the Franklin gage at rm 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 of total wastes receiving nitrification (P) in addition to secondary treatment at the sewage-treatment plants along the reach.

Model runs were conducted using three different rates of waste-water discharge corresponding to the rates expected for the years 1980, 1990, and 2000. In table 1 is given the name, location (by river mile), and expected flow rate for each of the sewage-treatment plants along the reach. The estimates of the waste water flow rates were based on information published by the Atlanta Regional Commission (Atlanta Regional Commission,

TABLE 1.—*The expected average daily flow in cubic feet per second, from waste-treatment plants discharging to the Chattahoochee River between Atlanta, Ga., and Whitesburg, Ga., 1980, 1990, and 2000*

Plant name	River mile	Expected average daily flow		
		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
Total		250	314	370

1977). All waste waters are assumed to have a DO concentration of 6 mg/L when discharged from the treatment plants.

In the model, the Chattahoochee River at the Atlanta gage is assumed to have 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 these temperature, BOD_u, ammonia, and DO values are based on those observed in June 1977.

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

For 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 1,800 ft³/s. The Atlanta Water Works (rm 300.62) withdraws 109 ft³/s, leaving a flow of 1,691 ft³/s to the confluence of the Chattahoochee River and Peachtree Creek (rm 300.52). Over the next 26.14 miles from this point, eight waste water treatment plants discharge effluent at the rates specified in table 1. The total flow from these plants is 314 ft³/s. In addition, a total of 93 ft³/s of tributary flow (the 7-day 10-year low flow of each tributary) enters the mainstem over the 65 miles between Peachtree Creek and the Franklin gage. Thus, the flow along the entire reach varies from 1,800 ft³/s down to 1,691 ft³/s and back up to 2,098 ft³/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, whereas 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 ft³/s in 1990, whereas the total flow from all eight plants is predicted to be 314 ft³/s. Thus, 48 percent of the wastes receive nitrification ($P = 48$). Given that Q_A is set at 1,800 ft³/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 with the run just described, except that the flow at the Atlanta gage was 850 ft³/s (resulting in a flow at Peachtree Creek of 741 ft³/s and a flow at the Franklin gage of 1,148 ft³/s). Given a Q_A of 850 ft³/s and a P 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 fig. 3). Thus the results of the two model runs just described may be summarized by an equation of the form

$$aQ_A + b = D,$$

where Q_A is the minimum flow at the Atlanta gage, in cubic feet per second, and D is the minimum DO over the reach, in milligrams per liter. The equation may be considered valid only for Q_A values in or near the range of 850 ft³/s to 1,800 ft³/s. Inserting the appropriate values for the slope (a) and the intercept (b) results, for the example described, in

$$0.0023Q_A + 0.89 = D.$$

RESULTS FROM THE DISSOLVED-OXYGEN MODEL

Pairs of runs (one for Q_A = 1,800 ft³/s; the other for Q_A = 850 ft³/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 providing only secondary treatment and those providing

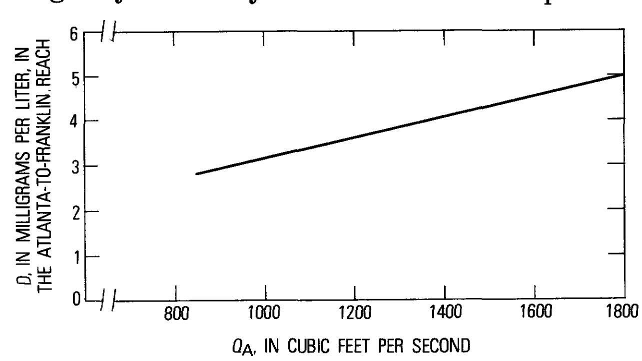

FIGURE 3.—Minimum dissolved-oxygen concentration (D) as a function of minimum flow at the Atlanta, Ga., gage (Q_A), given that 48 percent of the waste flow receives nitrification, for 1990 conditions.

secondary treatment plus nitrification (that is, the value of P) was varied. The results of these 14 runs are presented in the two graphs in figure 4. In figure 4a, the slope parameter (a) is 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 ($R^2 = 0.99$) and that between b and P, by a piecewise linear regression. (Each of the two regressions of b on P had an $R^2 = 0.99$.) 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 only minor importance. Thus, in the context of this study, the location of the plants providing nitrification may be ignored, and the treatment levels can be 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.

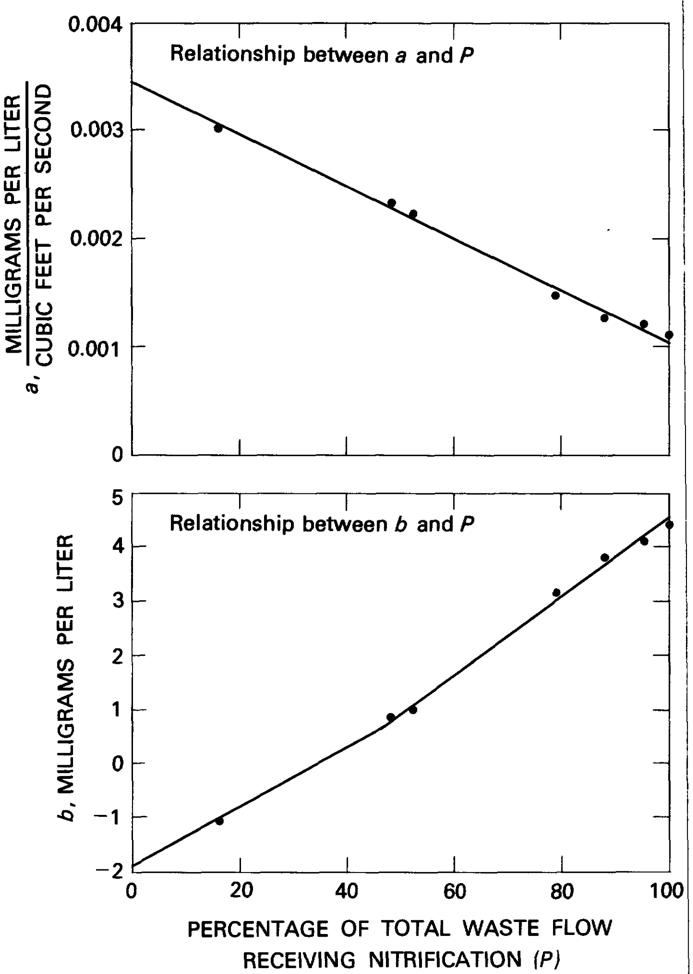

FIGURE 4. – Relationship of parameters of $aQ_A + b = D$ to percentage of total waste flow receiving nitrification (P).

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" (iso-dissolved-oxygen) curves.

The same procedure as that just described was used to approximate the relationship between D, P, and Q_A for the years 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 waste water flow can be seen by comparing the required amount of nitrification in 1980, 1990, and 2000 given, for example, $Q_A = 1{,}500$ ft³/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, and to 48 in 2000. Since the total waste flow is increasing (see table 1), this means that the flow receiving nitrification would have to be 55 ft³/s (0.22 × 250) in 1980, 113 ft³/s (0.36 × 314) in 1990, and 178 ft³/s (0.48 × 370) 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^* milligrams per liter. But, not all combinations of P and Q_A along these iso-DO curves are technically feasible. For example, from figure 6, setting Q_A equal to 1,800 ft³/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 simulation 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 hydrologic simulation model (HSM) was developed to determine, under a set of assumptions that shall be specified, the pattern of releases from Lake Sidney 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.

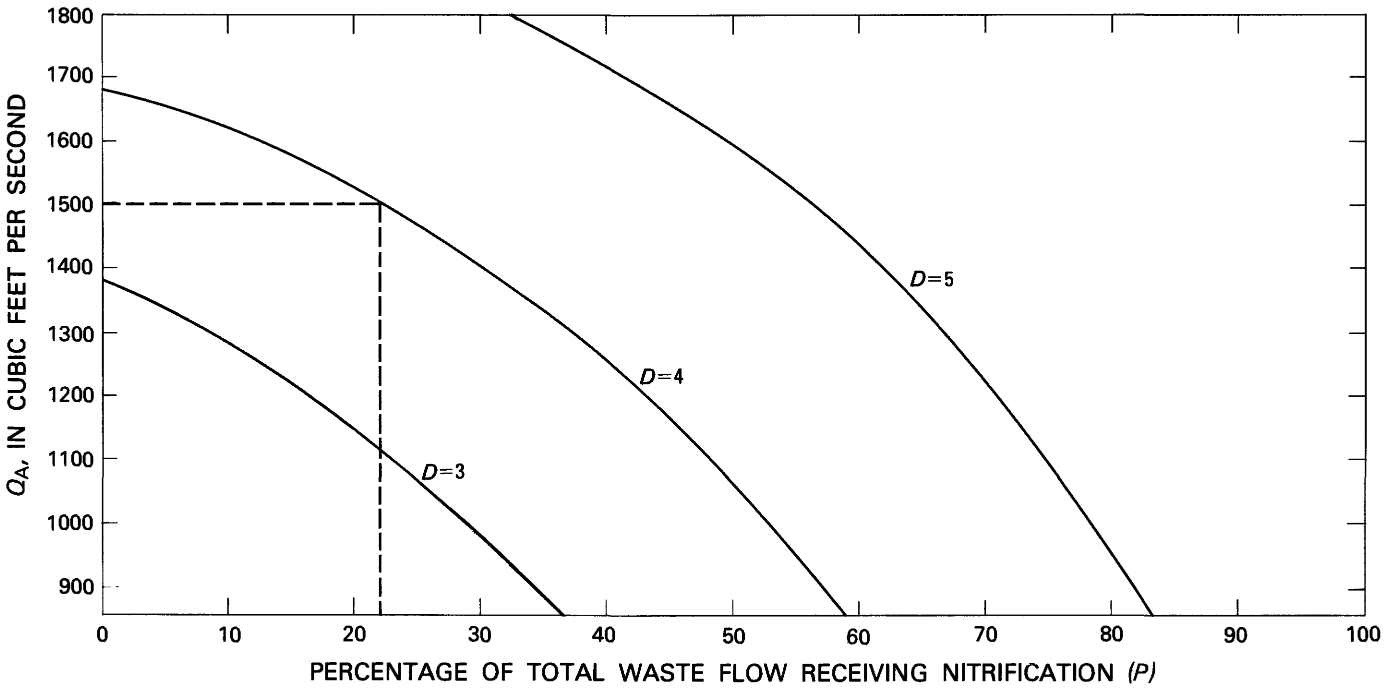

FIGURE 5. – Iso-dissolved-oxygen curves showing combinations of the percentage of total waste flow receiving nitrification (P) and minimum discharge at Atlanta, Ga., (Q_A) that are predicted to result in minimum dissolved-oxygen concentrations (D) of 3, 4, and 5 mg/L, for 1980 conditions.

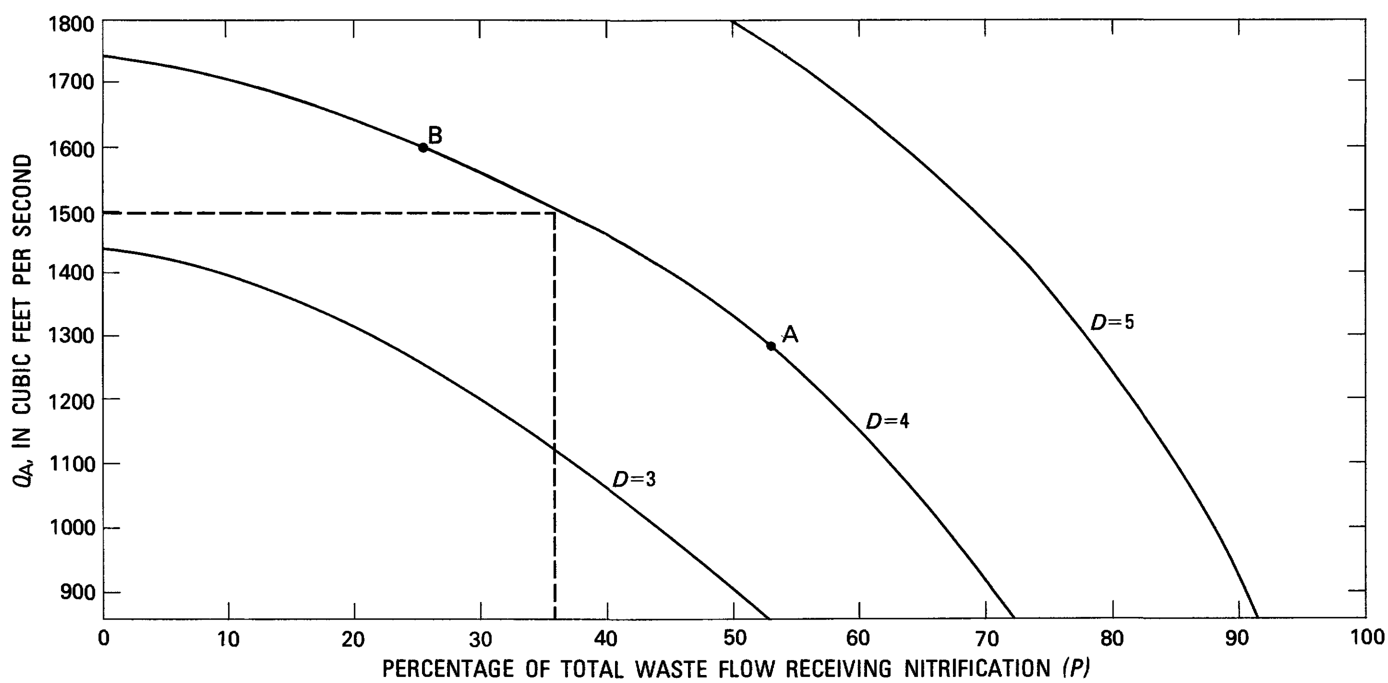

FIGURE 6. – Iso-dissolved-oxygen curves showing combinations of the percentage of total waste flow receiving nitrification (P) and minimum discharge at Atlanta, Ga., (Q_A) that are predicted to result in minimum dissolved-oxygen concentrations (D) of 3, 4, and 5 mg/L, for 1990 conditions.

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 Sidney Lanier and tributary flows to the Chattahoochee River 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** is defined as that rate of flow that can be provided at all times throughout a period in which the flows (for example, both into Lake Sidney Lanier and tributary flow between Buford Dam and Atlanta) are those that occurred in the most severe extended drought in the historic record. Similarly, **dependable peaking capacity** is defined as that peaking capacity that can be provided at all times throughout a period in which the flows are those that occurred in the most severe extended drought in the historic record. The most severe extended drought occuring in the study area during the 49-year historic record 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 to justify this definition of "dependable" on some economic grounds, it is accepted simply 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 HYDROELECTRIC 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 with the rate of flow of the water past the turbines; that is, it varies with the pattern of releases from Lake Sidney Lanier. The calculation of hydroelectric-power production is based on the following formula (Joe DeWitt, U.S. Army Corps of Engineers, Savannah District, oral commun. 1978):

$$Pe = 82.645(0.12390 + 0.000925\ (E - 1{,}055))\ Q,$$

where

Pe = power, in kilowatts,
E = pool elevation, in feet above sea level, and
Q = flow through the powerplant, in cubic feet per second.

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

The HSM is designed to first pattern the release of water from Lake Sidney Lanier so as to maximize the dependable summer-peak generating capacity of Buford

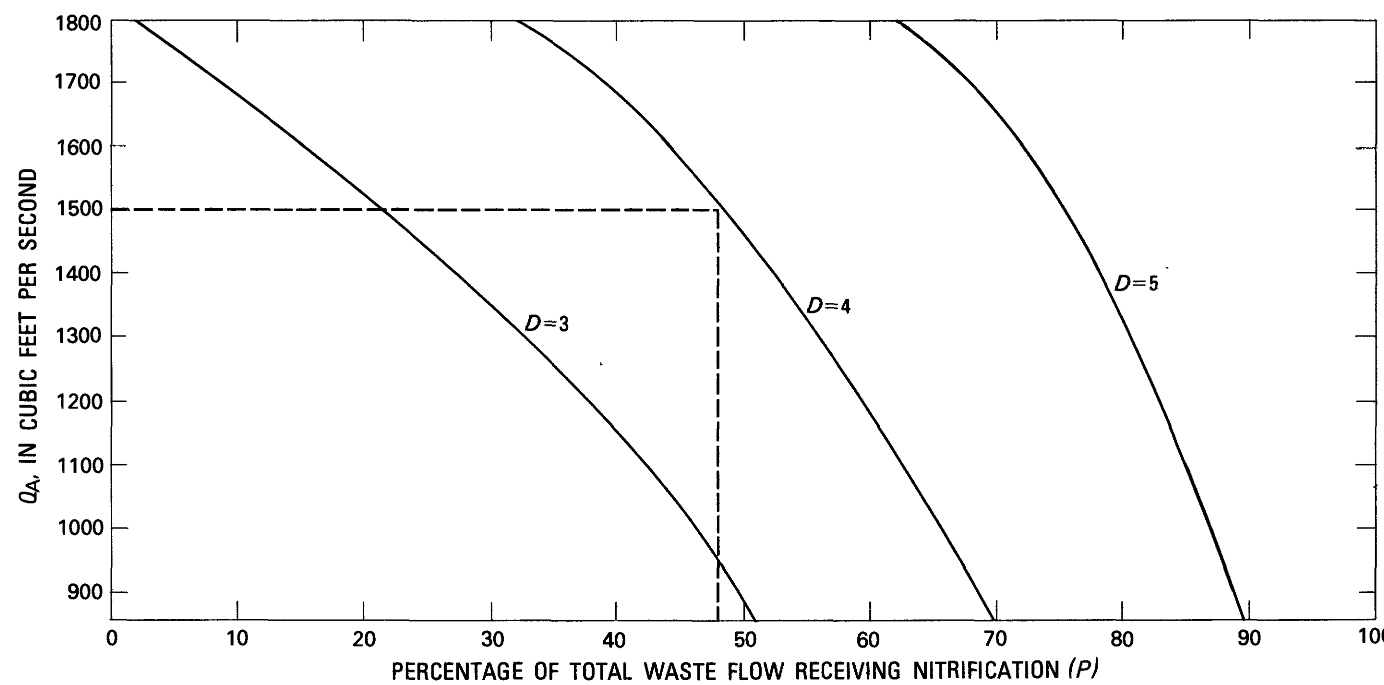

FIGURE 7.—Iso-dissolved-oxygen curves showing combinations of the percentage of total waste flow receiving nitrification (P) and minimum discharge at Atlanta, Ga., (Q_A) that are predicted to result in minimum dissolved-oxygen concentrations (D) of 3, 4, and 5 mg/L, for 2000 conditions.

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 used for the HSM are as follows:

Peak energy. All electric energy generated between 2 p.m. and 8 p.m. on weekdays.
Nonpeak 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 first to 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 greatest during the summer months. The electric-utility companies attempt to maintain sufficient generating capacity to meet the maximum peak demand, which will occur typically during the afternoon or evening of a summer weekday.

Hydroelectric turbines are especially useful for peaking purposes as they require very little startup time and can be brought online quickly. Because of this capability, the limited water available is not generally used to produce base power, except when water must be released to meet downstream needs or to vacate the flood pool.

The release of water from Lake Sidney Lanier is therefore assumed 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 (the Georgia Power Co.) that purchases power from the dam 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 Sidney Lanier is below 1,070 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 HYDROLOGIC SIMULATION MODEL

The HSM is designed to answer the following questions:

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 nonpeak electric-energy production, given this plan and Q_A?
5. What is the history of pool elevations of Lake Sidney 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 that maximizes the dependable peaking capacity of Buford Dam subject to the following flow and storage constraints:

$$dS_1/dt = T_1 - W_1 - Q_1, \tag{1}$$
$$Q_1 \leq 10{,}000, \tag{2}$$
$$S_1(t_0) = 8.35 \times 10^{10}, \tag{3}$$
$$S_1(t_f) = 4.69 \times 10^{10}, \tag{4}$$
$$S_1 \leq 8.35 \times 10^{10}, \tag{5}$$
$$Q_1 + T_2 \geq W_2, \tag{6}$$
$$ds_2/dt = Q_1 + T_2 - W_2 - Q_2, \tag{7}$$
$$S_2(t_0) = 0, \tag{8}$$
$$S_2(t_f) \geq 0, \tag{9}$$
$$S_2 \leq 1.09 \times 10^8, \text{ and} \tag{10}$$
$$Q_2 + T_3 - W_3 \geq Q_A. \tag{11}$$

The *decision variables* are all time varying, defined for values ≥ 0 and are as follows:

S_1 = storage in Lake Sidney Lanier, in cubic feet;
S_2 = storage in Morgan Falls Reservoir, in cubic feet;
Q_1 = release from Buford Dam (Lake Sidney Lanier), in cubic feet per second; and
Q_2 = release and spill from Morgan Falls Dam, in cubic feet per second.

The *initial storage conditions*, beginning of week 22, 1954, are

$S_1(t_0)$ = initial storage in Lake Sidney Lanier, in cubic feet, and
$S_2(t_0)$ = initial storage in Morgan Falls Reservoir, in cubic feet.

The *final storage conditions*, end of week 49, 1956, are

$S_1(t_f)$ = final storage in Lake Sidney Lanier, in cubic feet, and
$S_2(t_f)$ = final storage in Morgan Falls Reservoir, in cubic feet.

The *time-varying model parameters* are

T_1 = inflows to Lake Sidney Lanier, in cubic feet per second (constant over a week; values are those used in U.S. Army Corps of Engineers, 1977);
T_2 = tributary inflows between Buford Dam and Morgan Falls Dam, in cubic feet per second, (constant over the week; values equal one half of the tributary flow values reported in U.S. Army Corps of Engineers, 1977);

T_3 = tributary inflows Morgan Falls to the Atlantic Gage, in cubic feet per second (constant over the week, values equal one half of the tributary flow values reported in U.S. Army Corps of Engineers, 1977);

W_1 = withdrawals from Lake Sidney Lanier, in cubic feet per second (constant over week; varies with time of year and year of analysis; see table 2);

W_2 = withdrawals from the Chattahoochee River, Buford Dam to Morgan Falls Dam, in cubic feet per second (constant over week; varies with time of year and year of analysis; see table 3), and

W_3 = withdrawals from the Chattahoochee River, Morgan Falls Dam to the Atlanta gage, in cubic feet per second (constant over week, varies with time of and year of analysis; see table 4).

The *time constant model parameter* is

Q_A = Minimum flow at the Atlanta gage, in cubic feet per second.

The *model constraints* are as follows:

1. the continuity equation for Lake Sidney Lanier;
2. limitation on release from Buford Dam, 10,000 ft³/s, the channel capacity below the dam;
3. initial storage conditions for Lake Sidney Lanier, equal to initial storage for the same period in the U.S. Army Corps of Engineers base plan of operations;
4. final storage conditions for Lake Sidney Lanier, equal to final storage for the same period in the U.S. Army Corps of Engineers base plan of operation.
5. capacity constraint for Lake Sidney Lanier, 8.35×10^{10} ft³, corresponds to pool elevation of 1,070 ft. above sea level (normal pool elevation);
6. flows in the Buford Dam to Morgan Falls Dam reach, must be greater than or equal to the withdrawals in the reach at all times;
7. the continuity equation for Morgan Falls Dam;

8, 9. initial and final storage in Morgan Falls Reservoir (arbitrary);

10. capacity constraint on Morgan Falls Reservoir storage, and
11. flows at Atlanta gage, must be greater than or equal to the specified minimum flow Q_A, at all times.

RESULTS FROM THE HYDROLOGIC SIMULATION MODEL

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 nonpeak weekday hours in each week; and
4. release rate and power production for the 66 weekend (nonpeak) hours in each week.

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

To illustrate the results of the HSM, two examples are described. Both are based on water-supply withdrawals estimated for the year 1990 (tables 2, 3, and 4). In the first case, the required minimum flow at Atlanta (Q_A) is set at 1,290 ft³/s. Values for two different weeks of operation are considered in detail in this comparison: those of week 33 (mid-August), 1954, and week 40 (early October), 1954. In both weeks, the tributary flows (T_2 and T_3) were equal to zero. The releases and hydroelectric-power production under each run are given in table 5. The release patterns 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 the

TABLE 2.—*Withdrawals, in cubic feet per second, from Lake Sidney Lanier, Ga.*

Weeks	Year 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, in cubic feet per second, from Chattahoochee River, Ga., Buford Dam to Morgan Falls Dam*

Weeks	Year 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, in cubic feet per second, from Chattahoochee River, Ga., Morgan Falls Dam to the Atlanta gage*

Weeks	Year 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.–*Hydrologic-simulation-model results of water discharge and electric-power production at Buford Dam, Ga., for 1990 conditions*

Minimum flow at the Atlanta gage (Q_A)	1,290 ft³/s	1,600 ft³/s
Week 33, 1954		
Discharge, in cubic feet per second:		
Average	2,290	1,780
During:		
Peak hours	10,000	6,480
Nonpeak hours	198	198
Weekends	1,070	1,380
Electric-energy production, in megawatt-hours:		
Total	4,270	3,500
Peak	3,330	2,320
Nonpeak, weekdays	160	160
Nonpeak, weekends	780	1,020
Week 40, 1954		
Discharge, in cubic feet per second:		
Average	1,510	1,820
During:		
Peak hours	5,760	6,810
Nonpeak hours	170	170
Weekends	1,030	1,340
Electric-energy production, in megawatt-hours:		
Total	2,720	3,360
Peak	1,860	2,250
Nonpeak, weekdays	130	130
Nonpeak, weekends	730	980

time of the week: weekend flows increase and peak flows either decrease (if summer) or increase (if nonsummer). 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.

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 1,600 ft³/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 drawdown during the summer-recreation season than will a high Q_A. From the standpoint of recreation, a plan of operation with Q_A = 1,600 ft³/s has a more desirable result than does a plan with Q_A = 1,290 ft³/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 (1,600 ft³/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 Sidney Lanier is not allowed to fall below 1.07 million acre-feet (pool elevation 1,043.9 ft), which is 56 percent of the storage at normal pool elevation (1,070 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 1,290 ft³/s for 1990. Given this minimum flow requirement, it is possible to fully utilize the generating turbines with a release of 10,000 ft³/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 ft³/s and a pool elevation of 1,043.9 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.

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 nonpeak power production, and the weekly pool elevation of Lake Sidney Lanier upon which to base estimates of the change in benefits given a change in Q_A.

TABLE 6.–*Hydrologic-simulation-model results, for 1980, 1990, and 2000*

Year	1980	1990	2000
Maximum sustainable value of Q_A[1]	1670	1600	1230
Dependable peaking capacity at maximum sustainable Q_A[2]	66	66	58
Value of Q_A associated with maximum dependable peaking capacity[1]	1380	1290	870
Maximum value of dependable peaking capacity[2]	98	98	97

[1] In cubic feet per second.
[2] In megawatts.

ESTIMATION OF COSTS: BENEFITS FOREGONE AND WASTE-TREATMENT COSTS

In this section, the method used to obtain estimates of the recreation and hydroelectric benefits associated with a given Q_A under (here, 1954-56) drought conditions is described first. 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 of the total waste flow receiving nitrification (*P*).

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 Sidney Lanier for water-quality maintenance purposes, this lost capacity will have to be replaced (it is assumed) by an electric utility company in the private sector of the economy. The Georgia Power Co. is currently constructing a hydroelectric pump-storage peaking facility (its "Rocky

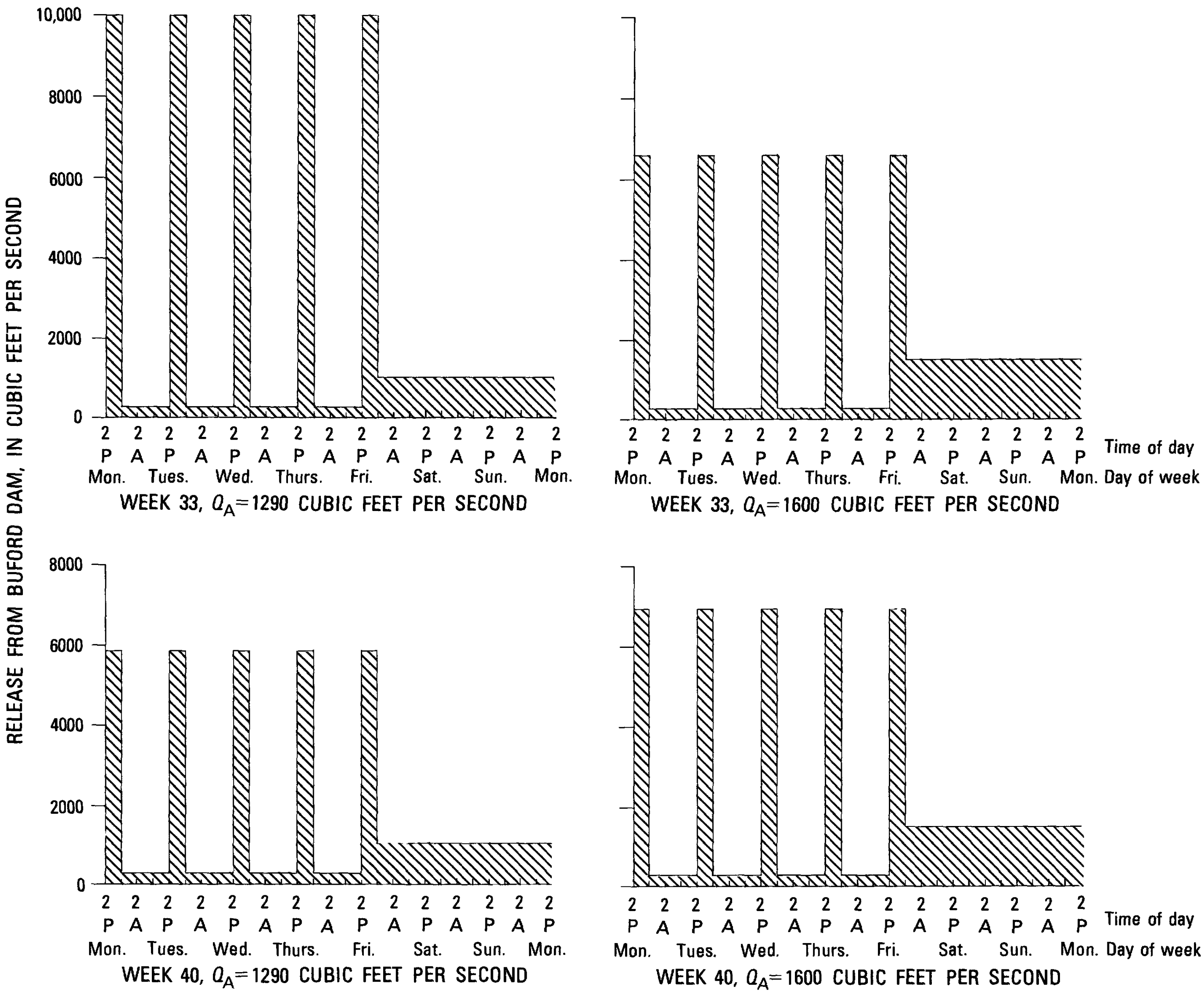

FIGURE 8.—Simulated releases at Buford Dam, Ga., during weeks 33 and 40 of 1954, given a minimum flow at Atlanta (Q_A) of 1,290 ft³/s and 1,600 ft³/s, for 1990 conditions.

Mountain Project") and is amortizing the capital cost of this facility using a discount rate of 11.24 percent (C.R. Thrasher, Georgia Power Co., written commun., June 5, 1978). Though the choice of a discount rate is somewhat subjective and requires a value judgment, 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 Sidney Lanier are based on data obtained from a U.S. Army Corps of Engineer publication (1977). According to the Corps of Engineers, the recreation benefits obtained from Lake Sidney Lanier vary with both the pool elevation of the reservoir and the season of the year. They have published (1977) estimates of both the peak- and the offpeak-season recreation associated with pool elevations ranging from 1,055 to 1,080 feet above sea level. For example, the Corps of Engineers estimated that a pool elevation of 1,070 feet has associated peak-season benefits of $17,820,900 and offpeak 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 offpeak-season benefits were uniformly distributed over the 30 weeks from October 1 through April 30. Thus, a pool elevation of 1,070 feet would have associated with it recreation benefits of $810,041 per week during the peak season and $433,703 per week during the offpeak season. The weekly recreation benefits associated with each pool elevation are graphed in figure 10.

The HSM provided the weekly pool elevation of Lake Sidney 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 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 Sidney 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.

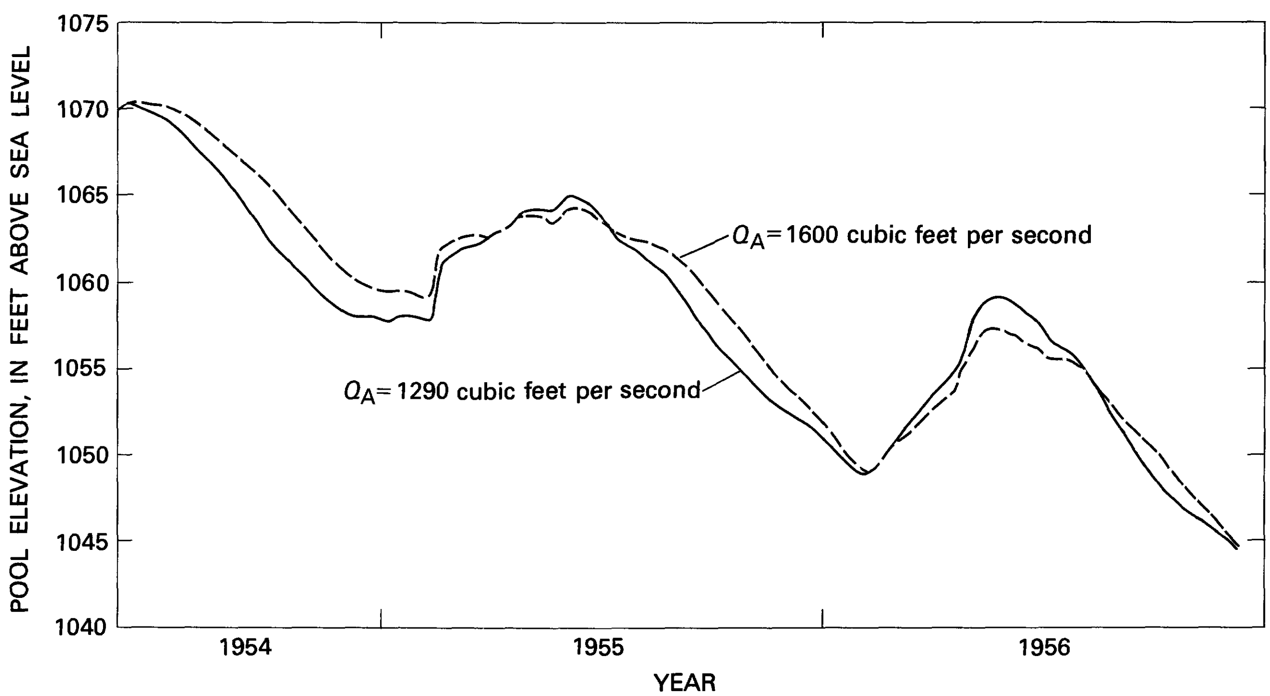

FIGURE 9.—Pool elevation of Lake Sidney Lanier over the period of simulation, given that the minimum flow at Atlanta, Ga., (Q_A) is set at 1,290 ft³/s and 1,600 ft³/s, for 1990 conditions.

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, a kilowatt-hour) 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 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 the generation of electric energy during periods of peak demand. Though it has been assumed herein that the dam provides no *dependable* base generating capacity, it does produce some energy during nonpeak hours because water is sometimes released during these hours to satisfy downstream flow requirements. Any nonpeak 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.

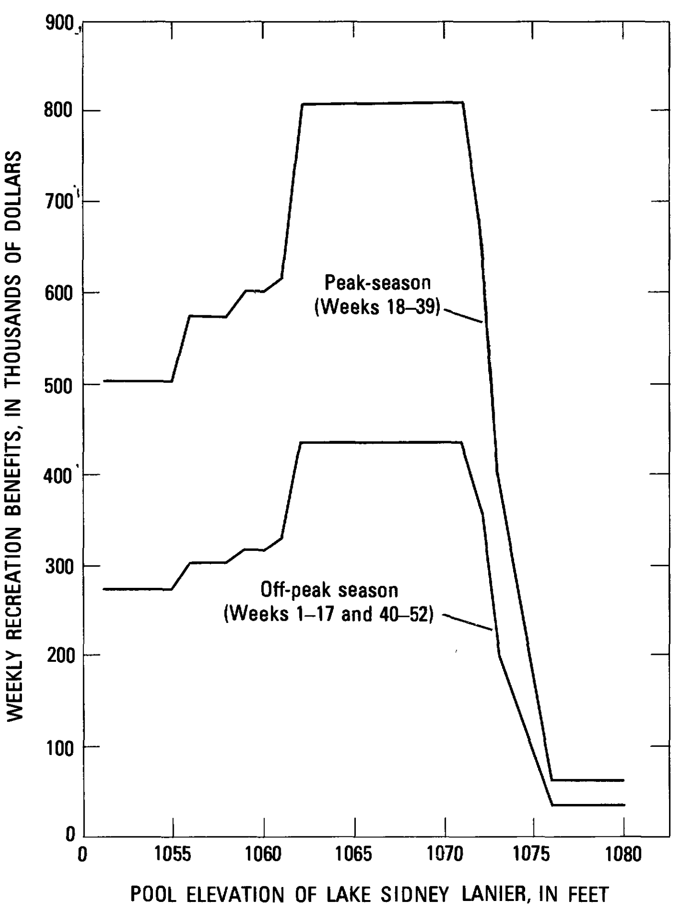

FIGURE 10.–Benefits from recreation on Lake Sidney Lanier, given various pool elevations.

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 because of a change in its operating rules could be replaced by a facility similar in cost to the Georgia Power Co.'s 675-MW "Rocky Mountain" facility, which is scheduled to come online in 1983. Using data obtained from the Georgia Power Co. (C.R. Trasher, Georgia Power Co., written commun., 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 Commisison to the U.S. Army Corps of Engineers (1977), the energy cost of electricity produced by coal-fired thermal electric powerplants 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 Co.'s "Rocky Mountain" facility, such electricity must be assigned a higher energy value. The Georgia Power Co. estimates that 1.4 kWh of electricity must be expended in pumping for storage (in offpeak periods) to generate 1.0 kWh of electricity in peak periods (Georgia Power Co., 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 mill/kWh (=7.75 mills/kWh × 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 U.S. Army Corps of Engineers has assumed that the alternative to producing peak energy at Buford Dam is to produce it by a coal-

TABLE 7.—*Hydrologic simulation-model results and estimated benefits for 1990, given certain minimum flows at Atlanta, Ga., under 1954-56 drought conditions.*

	Minimum flows, in cubic feet per second	
Atlanta gage	1,290	1,600
Confluence of Chattahoochee River and Peachtree Creek	1,180	1,490
	Average energy output, in megawatt-hours per year	
Annual	132,500	134,400
Annual nonpeak	34,500	45,800
Annual peak	98,000	88,600
	Dependable peaking capacity, in megawatts	
(See minimum flows given for Atlanta)	98.1	65.9
	Benefits, in millions of dollars per year	
Nonpeak energy	.27	.35
Peak energy	1.06	.96
Dependable peaking capacity	2.29	1.54
Recreation	24.38	25.00
Total	28.00	27.85

fired thermal electric powerplant. 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 nonpeak 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 ($Q_A = 1{,}290$ ft^3/s and $Q_A = 1{,}600$ 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 1,600 ft^3/s from 1,290 ft^3/s are nonpeak-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 1,600 ft^3/s from 1,290 ft^3/s in 1990 is estimated to be $150,000/per year.

ESTIMATION OF AVERAGE ANNUAL BENEFITS

The method of estimating the benefits derived from Buford Dam under different operating rules given 1954–56 drought conditions is described in the preceding section. 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.

The estimates of the average annual benefits to be obtained under different minimum flows at Atlanta would be more appropriately based on a simulation of dam operations over the entire available hydrologic record, including the worst-case drought. Such a simulation, however, would be an extended task. Also, only the *change* in average annual benefits (that is, benefits foregone) as a result of a change in Q_A is of interest here. Thus, the estimates of the benefits foregone associated with a change in Q_A are 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, nonpeak-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 both of the flows in that year and of 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 (1,600 ft^3/s) rather than a low value (1,290 ft^3/s) does not have much effect on reservoir operations or on benefits. With plentiful water, it becomes possible to simultaneously satisfy the objectives of maximizing peak-energy production, holding lake levels stable (near 1,070 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 Sidney Lanier was 2,229 ft^3/s, whereas during June 1954 through May 1955, the average flow was 1,311 ft^3/s. After adjusting for storage, the reported (35-year) average flow at the U.S. Geological Survey gage below Buford Dam is 2,168 ft³/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 per week) is 10,000 ft³/s; and
3. Reservoir storage is not to exceed 1.917 million acre-ft (at 1,070 ft pool-elevation.)

The simulation was conducted for Q_A values of 1,290 ft³/s and 1,600 ft³/s.

The annual recreation benefits associated with the two minimum flows differ by less than $1,000. The results of the simulation associate a minimum pool elevation of 1,065.6 ft with a Q_A of 1,290 ft³/s and a minimum elevation of 1,064.6 with a Q_A of 1,600 ft³/s. As can be seen by referring to figure 10, recreation benefits are nearly the same for all elevations between 1,064 and 1,071 ft.

Peak-energy production is nearly the same given a Q_A of either 1,290 ft³/s or 1,600 ft³/s. In both cases, there is a 10,000 ft³/s flow through the power plant for 30 hrs per week during the full year at heads that 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 $2,000.

Base-energy production is also virtually the same for both values of Q_A. Whether Q_A is set at 1,290 ft³/s or at 1,600 ft³/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 1,070 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 hydrologic conditions, an increase in Q_A to 1,600 ft³/s from 1,290 ft³/s decreases the dependable-peaking-capacity benefits by $0.75 million per yr (a 32,300 kW loss in capacity multiplied by the estimated capacity value of $23.34/kW/yr), as happens under 1954–56 drought conditions.

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 1,600 ft³/s from 1,290 ft³/s the increase in the peak- and nonpeak-energy benefits and the recreation benefits ranges from a total of $0.56 million per year 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; but, for simplicity, this assumption was adopted, and the relationship between Q_A and average annual benefits foregone, as graphed 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 (1977).

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 of the total waste flow receiving nitrification (P) 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-round, 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.

The data presented in table 8 were then used to develop estimates of the minimum annual cost of submitting any given percentage of the total waste flow to nitrification. This was accomplished by identifying the plant or combination of plants that could provide nitrificaton 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.

THE REREGULATION PROJECT

The U.S. Army Corps of Engineers has considered a project involving the construction of a reregulation structure on the Chattahoochee River just below Buford Dam and the dredging of the reservoir behind Morgan Falls Dam. This project would permit a more steady (and higher minimum) flow at Atlanta for any given 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.

A version of the HSM in which it is assumed that this project is completed is described in appendix A. The estimated costs of the project were obtained from a U.S. Army Corps of Engineers publication (1977). As is illustrated in the appendix (fig. 16), these costs exceed the project benefits, whether peak generating capacity is assigned a value of \$23.34/kW/yr or of \$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 it received no further consideration here.

LEAST-COST METHOD OF PRODUCING A GIVEN MINIMUM DISSOLVED-OXYGEN CONCENTRATION

The problem at hand can be usefully considered 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 of the total waste load receiving nitrification (P) 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 that are potentially capable of producing the indicated minimum DO concentration in 1990. If it is desired to "produce" a

TABLE 8.—*The average daily flow from waste-treatment plants discharging to the Chattahoochee River between Atlanta, Ga., and Whitesburg, Ga., and the annualized cost of adding a nitrification process to the plants (in First-quarter 1976 dollars)*

Plant name	River mile	1980 Average flow (ft³/s)	1980 Annual cost ($1,000)	1990 Average flow (ft³/s)	1990 Annual cost ($1,000)	2000 Average flow (ft³/s)	2000 Annual cost ($1,000)
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

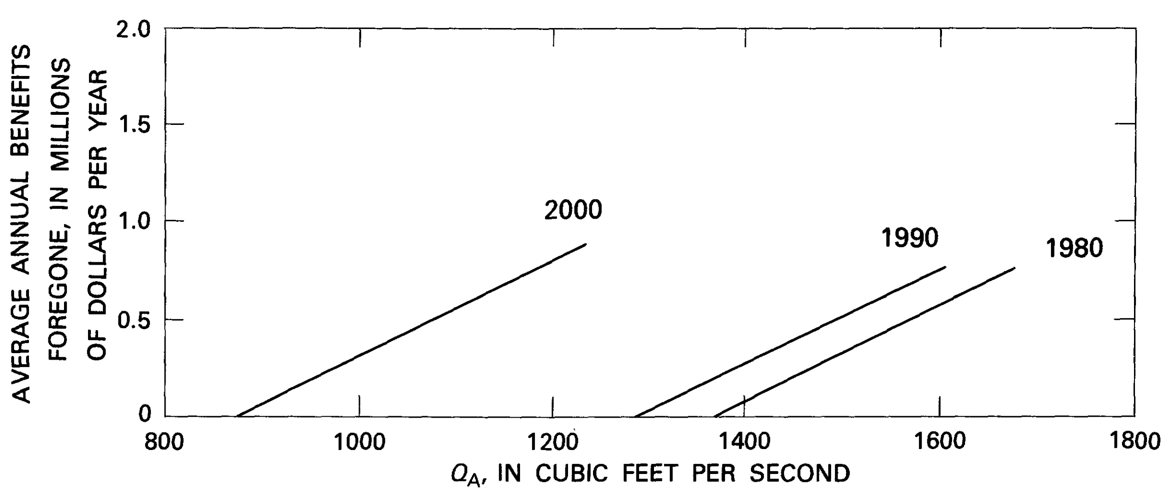

FIGURE 11.—The relationship between average annual benefits foregone and minimum flow at Atlanta (Q_A) for 1980, 1990, and 2000.

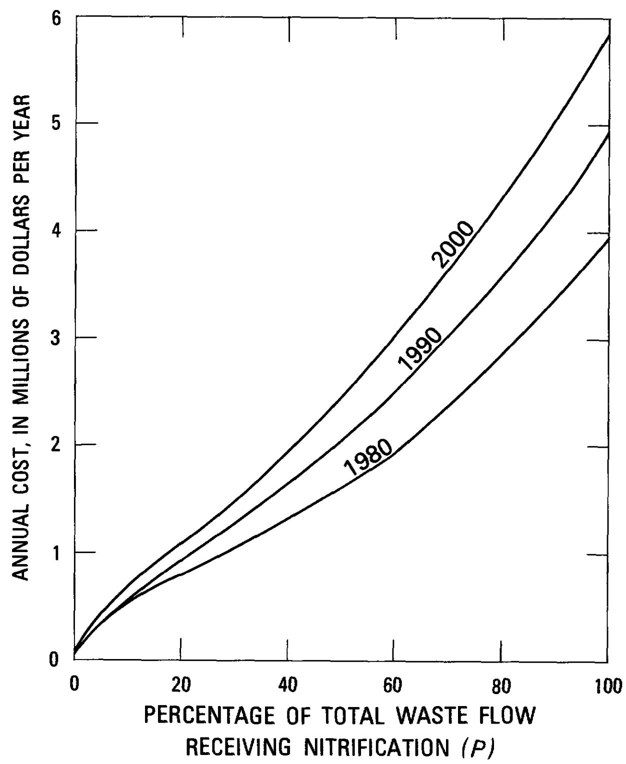

FIGURE 12. – The estimated annual cost of adding a nitrification process to secondary waste-treatment plants, as a function of the percentage of the total waste flow receiving nitrification (P), for 1980, 1990, and 2000.

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 of 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 1,670 ft^3/s, 1,600 ft^3/s, and 1,230 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 1,600 ft^3/s on Q_A, because the *maximum necessary* Q_A is only 1,430 ft^3/s. However, a minimum DO concentration of 4 mg/L requires, if $P=0$, a minimum flow of about 1,750 ft^3/s, whereas the *maximum sustainable* Q_A is only 1,600 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

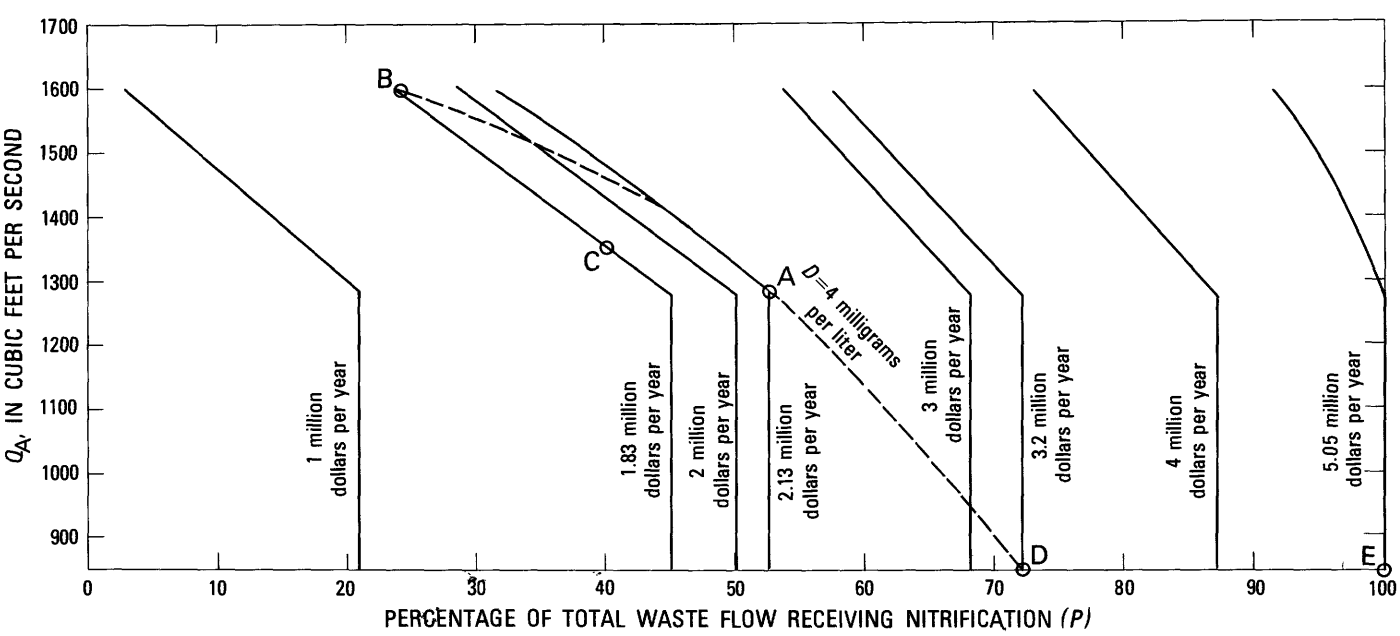

FIGURE 13. – An illustration of the method of determining the least-cost combination of the percentage of waste flow receiving nitrification (P) and the minimum flow at Atlanta, Ga., (Q_A), required to produce a minimum dissolved-oxygen concentration of 4 mg/L, for 1990. Costs are in million dollars per year.

nitrification and of dependable peak generating capacity. Consider, for example, point A in figure 6; here $P=53$ and $Q_A=1{,}290$ ft³/s. From figure 11, it can be seen that, given this Q_A, no benefits are 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 ($P=53$, $Q_A=1{,}290$ ft³/s) has associated with it a total cost of 2.13 million dollars per year. Next consider point B in figure 6: here, $P=24$ and $Q_A=1{,}600$ ft³/s. From figure 11, it can be seen that at a Q_A of 1,600 ft³/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 nitrifiction, 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, the combination of P and Q_A that will "produce" a given minimum DO concentration at least cost can be found. For 1990, the least-cost method of attaining a minimum DO concentration of 4 mg/L was determined to be 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 that 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 fig. 6) has an associated total cost of 1.83 million dollars per year. Every combination of P and Q_A along the iso-cost curve that passes through point B has an associated total cost of 1.83 million dollars per year. For example, at point C ($P=40$, $Q_A=1{,}360$ ft³/s) on this iso-cost curve, the peak-generating-capacity benefits foregone, given a Q_A of 1,360 ft³/s, are (from fig. 11) 0.16 million dollars per year; the additional treatment cost, given that 40 percent of the wastes are to receive nitrification, is (from fig. 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, because of increased treatment costs. Note also that for any given level of P, total costs will increase with Q_A owing to increased benefits foregone, but such increases will occur only for those Q_A greater than 1,290 ft³/s (in 1990). For those Q_A less than 1,290 ft³/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 1,290 ft³/s (in 1990) and represents only the nitrification costs associated with that level of P. Finally, note that as *both* 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 in 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 ($P=24$, $Q_A=1{,}600$ ft³/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 for producing the three minimum DO concentrations in 1980 and 2000. In table 9 are also presented the separate components of total cost which are benefits foregone and the cost of adding the nitrification process to the waste-treatment plants.

Note that in a comparison of the least-cost combinations of a given DO standard across years, the DO standard of 5 mg/L provides the only case examined where

TABLE 9. – *Combinations of percentage of wastes receiving nitrification and minimum flow at Atlanta, Ga., that will provide minimum dissolved-oxygen concentrations of 3, 4, and 5 mg/L at least-cost, for 1980, 1990, and 2000*

Minimum dissolved-oxygen concentration (mg/L)	Percentage of wastes receiving nitrification (P)	Minimum flow at Atlanta (Q_A) (ft³/s)	Costs, in million dollars per year		
			Nitrification	Benefits foregone	Total
		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

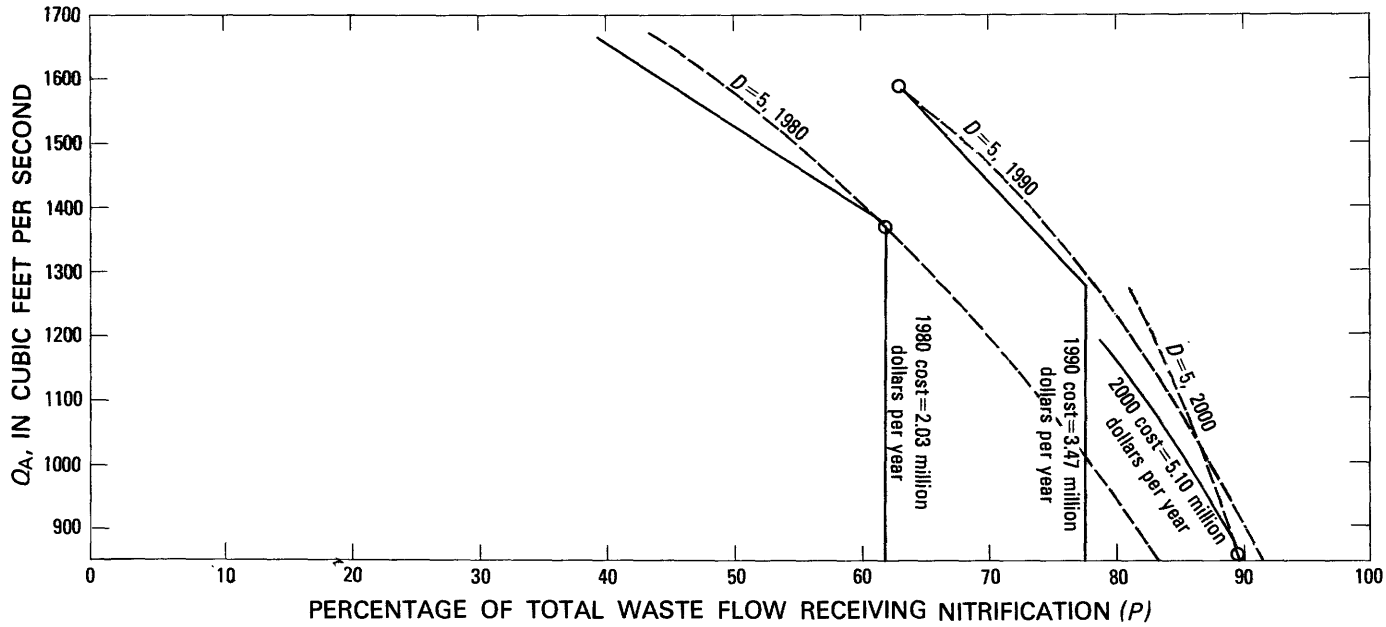

FIGURE 14.–Illustration of the solution for least-cost combinations of percentages of wastes receiving nitrification (*P*) and minimum flow at Atlanta, Ga., (Q_A) necessary to produce a minimum dissolved-oxygen concentration of 5 mg/L, for 1980, 1990, and 2000. Costs, in millions of dollars.

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 the maximum sustainable in 1980 and 1990 and then be reduced to 870 ft^3/s in 2000.

The solutions 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." This 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 operated in 1980 and 2000.

This suggests two related questions: First, how sensitive is the least-cost solution to the value of the parameters that determine the slope of the iso-cost curves? Second, 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 either at 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 either that Buford Dam 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 as a result of the loss of such capacity will be greater at each Q_A that 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 beneath 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 that cause such a switch in the least-cost combination of P and Q_A are presented in table 10.

TABLE 10.—*Costs, in first-quarter 1976 dollars per kilowatt-hour per year, of dependable peak generating capacity above which the indicated minimum dissolved-oxygen (DO) concentration can be achieved at least cost by operating Buford Dam, Ga., so as not to forego benefits from dependable peak generating capacity*

Minimum dissolved-oxygen concentration (mg/L)	Year 1980	Year 1990	Year 2000
3	(1)	69	21
4	34	33	22
5	17	25	16

[1] It is not necessary to forego peak generating capacity even if Q_A is set at the maximum necessary (1,380 ft³/s) to achieve a minimum DO concentration of 3 mg/L.

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" hydroelectric-power pump-storage facility. Consequently, the least-cost combination requires that no dependable peak generating capacity be foregone in order to provide a minimum DO concentration of either 3, 4, or 5 mg/L in 2000 and to provide a minimum DO concentration of 5 mg/L in 1980. But, note that our estimate of $23.34/kW/yr is close to those costs that would require 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 (1977) 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-coast 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 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 1,380 ft³/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 that would result from the use of an erroneous estimate of the cost of peak generating capacity.

The economic-efficiency losses that would result if the cost of peak generating capacity were actually $49.35/kW/yr but the least-cost combination were calculated and selected using an estimated cost of $23.34/kW/yr are listed in table 11; 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 1,600 ft³/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 1,290 ft³/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 per year efficiency loss given a 5 mg/L-DO standard in 1990. This efficiency loss would result from too little nitrification and too much peak generating capacity lost relative to the "correct" least-cost combination.

The economic-efficiency losses that would result if the cost of peak generating capacity were actually $23.34/kW/yr but the least-cost combination were calculated and selected using an estimated cost of $49.35/kW/yr are listed in table 12. 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 1,290 ft³/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 1,600 ft³/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.

TABLE 11.—*Economic-efficiency loss, in million dollars per year, if the least-cost combination of the percentage of wastes receiving nitrification (P) and the minimum flow at Atlanta, Ga., (Q_A), in cubic feet per second, is selected under the assumption that the cost of peak generating capacity is \$23.34/kW/yr but the actual cost is \$49.35/kW/yr. for 1980, 1990, and 2000*

Minimum dissolved-oxygen concentration (mg/L)	Least-cost combination: Calculated P	Calculated Q_A	Correct P	Correct Q_A	Economic efficiency loss
1980					
3	0	1,380	0	1,380	0.00
4	0	1,670	31	1,380	.37
5	62	1,380	62	1,380	.00
1990					
3	0	1,430	0	1,430	0.00
4	24	1,600	52	1,290	.54
5	63	1,600	78	1,290	.80
2000					
3	52	870	52	870	0.00
4	70	870	70	870	.00
5	90	870	90	870	.00

TABLE 12.—*Economic-efficiency loss, in million dollars per year, if the least-cost combination of the percentage of wastes receiving nitrification (P) and the minimum flow at Atlanta, Ga., (Q_A), in cubic feet per second, is selected under the assumption that the cost of peak generating capacity is \$49.35/kW/yr but the actual cost is \$23.34/kW/yr, for 1980, 1990, and 2000*

Minimum dissolved-oxygen concentration (mg/L)	Least-cost combination: Calculated P	Calculated Q_A	Correct P	Correct Q_A	Economic efficiency loss
1980					
3	0	1,380	0	1,380	0.00
4	31	1,380	0	1,670	.42
5	62	1,380	62	1,380	.00
1990					
3	0	1,430	0	1,430	0.00
4	52	1,290	24	1,600	.30
5	78	1,290	63	1,600	.04
2000					
3	52	870	52	870	0.00
4	70	870	70	870	.00
5	90	870	90	870	.00

Note that, given the two estimates of peak generating capacity cost, only three cases have 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 in only 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 cost of \$49.35/kW/yr. However, we believe that it is inappropriate to assume that any peak generating capacity lost at Buford Dam 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" hydroelectric-power pump-storage facility. The Georgia Power Co. apparently found hydroelectric-power 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 that 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, constraints may exist in the form of laws or regulations that restrict the range of choice of P and (or) Q_A. The questions then become 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 indicated 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 that passes through point D in figure 13—3.2 million dollars per year. 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

TABLE 13.–*Percentages of wastes that must receive nitrification to provide minimum dissolved-oxygen concentration of 3, 4, and 5 mg/L at least-cost, given that the minimum flow at Atlanta, Ga., is constrained to 860 ft³/s for 1980, 1990, and 2000*

Minimum dissolved-oxygen concentration (mg/L)	Percentage of wastes receiving nitrification (P)	Minimum flow at Atlanta (Q_A) (ft³/s)	Costs, in million dollars per year		
			Nitrification	Benefits foregone	Total
		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

labeled points in figure 13.) The least-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 ft³/s, are also described in table 13.

As another example of a constraint and its associated cost, suppose that a requirement existed that Q_A be set at 860 ft³/s *and* that all wastes receive nitrification ($P=100$). Because no dependable-peak-generating-capacity benefits are 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 15. Note that, from figures 5 through 7, the constraint that $P=100$ and $Q_A=860$ ft³/s will result in a minimum DO concentration that 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 non-monetary, tangible or intangible) that might result from the constraint.

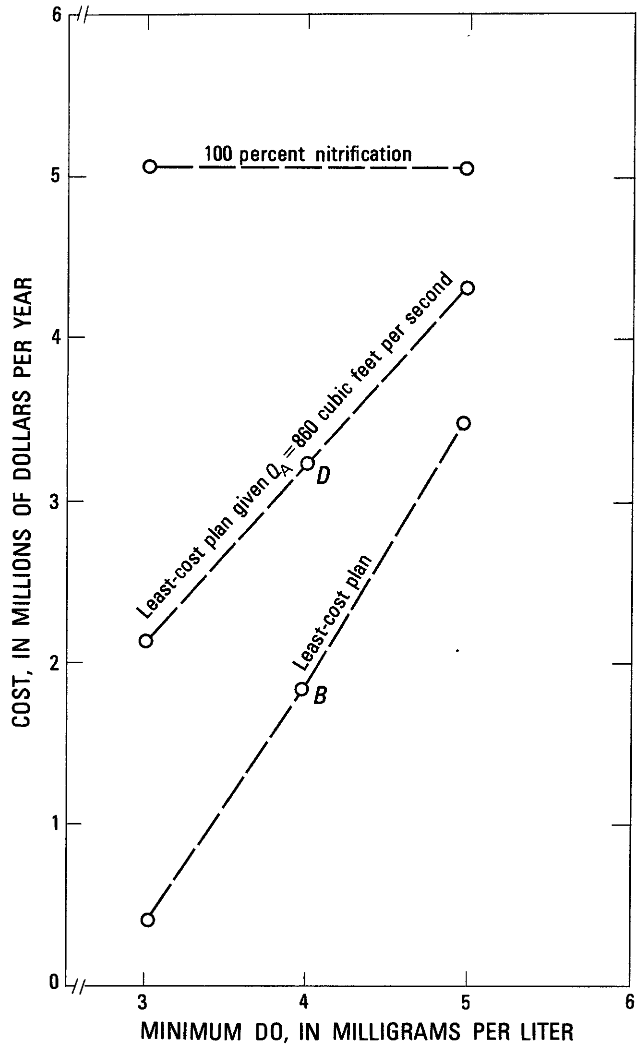

FIGURE 15.–Costs (benefits foregone plus added waste-treatment cost) of attaining various minimum dissolved-oxygen (DO) concentrations under different policies, in 1990. Note that cost is independent of the dissolved-oxygen standard, given a constraint of 100 percent nitrification.

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 U.S.G.S. 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 necessary 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 that 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 U.S.G.S. data and models that could be used to derive the DO production relationship. Another objective was to demonstrate how the results of a U.S.G.S. Intensive River Quality Assessment could be applied to a water-quality management problem.

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

In regard to the Chattahoochee River, the results indicate that for certain DO standards and between now and 2000 the waste-assimilation 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 because of 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 taxpayer 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 least-cost method for attaining a given minimum DO concentration has distributional or equity implications that have not been considered in this study.

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APPENDIX A—ANALYSIS OF THE REREGULATION PROJECT

If the proposed reregulation structure were built just below Buford Dam (capacity 8,400 acre-feet) and if the Morgan Falls reservoir were dredged to a capacity of 3,500 acre-feet, then more peak hydroelectric power could be produced given any required minimum flow at the Atlanta gage. By storing more of the water released from Buford Dam during peaking hours, most or all the water-supply and minimum-flow needs throughout the entire week can be met.

The HSM was modified to simulate this situation, and 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

$$dS_R/dt = Q_1 - Q_R \tag{12}$$
$$S_R(t_0) = 0, \tag{13}$$
$$S_R(t_f) \geq 0, \text{ and} \tag{14}$$
$$S_R \leq 3.66 \times 10^8. \tag{15}$$

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

$$Q_R + T_2 \geq W_2, \tag{6a}$$
$$dS_2/dt = Q_R + T_2 - W_2 - Q_2, \text{ and} \tag{7a}$$
$$S_2 \leq 1.52 \times 10^8. \tag{10a}$$

Added and changed constraints are

12. continuity equation for the reregulating reservoir;
13. and 14. initial and final storage in reregulating reservoir (arbitrary);
15. capacity constraint for reregulating reservoir, 3.66×10^8 ft^3 = 8,400 acre feet;
6a. the withdrawals below Buford Dam but above Morgan Falls Dam, must be satisfied by the release from the reregulating reservoir plus tributary flows;
7a. continuity equation for Morgan Falls reservoir, the inflow being the release from the reregulating reservoir plus tributary flow minus withdrawals; and
10a. the capacity of Morgan Falls reservoir, 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 16 shows the dependable-peaking-capacity benefits as a function of Q_A with and without the reregulating structure and Morgan Falls reservoir dredging. Also these benefits minus the cost of these improvements are shown in this figure.

According to the U.S. Army Corps of Engineers' Lake Sidney Lanier restudy (1977), the capital cost of the reregulating structure is $11.50 million and the operation and maintenance costs are $65,800 per year. Based on a discount rate of 10 percent and a life of 100 years, the annualized cost of the facility is $1.22 million per year. The Corps reports the initial cost of the Morgan Falls reservoir dredging is $1.65 million and annual maintenance-dredging costs are $15,000/per year. Based on a 10 percent discount rate and a 100 year life, the annualized cost of the Morgan Falls reservoir dredging is $0.18 million per year. Thus, the annual cost of both projects is $1.40 million per year.

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 cost of dependable peaking capacity is $23.34/kW/yr. Even if this cost 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.

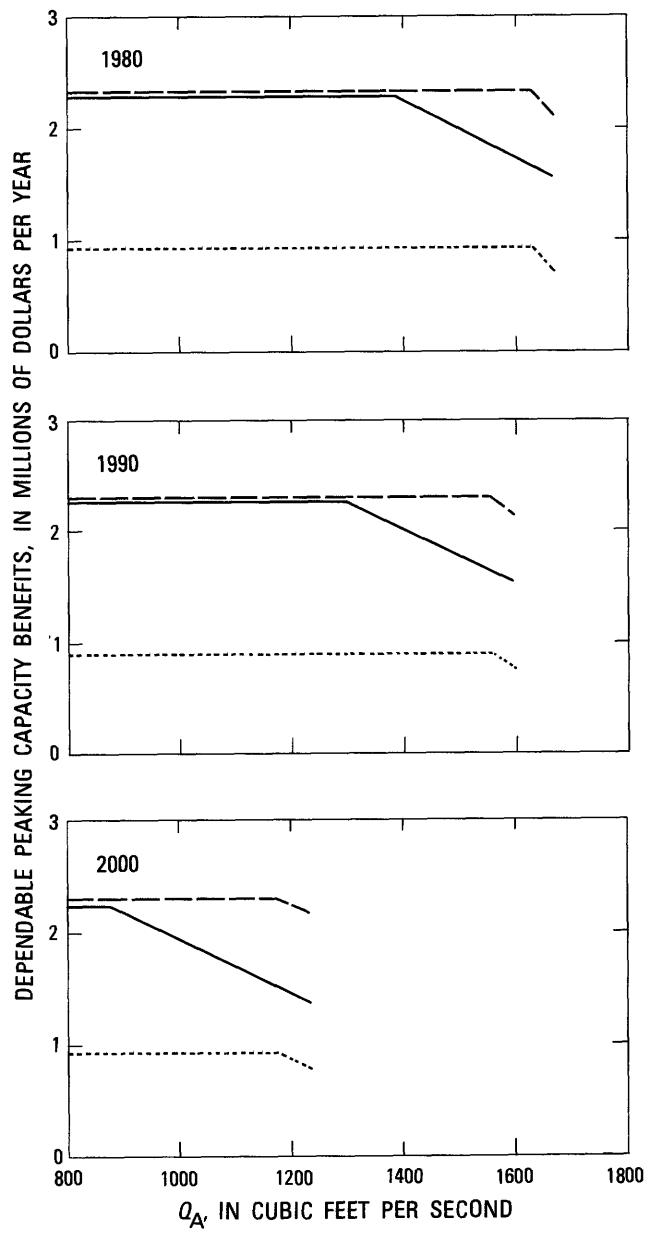

FIGURE 16.—The relationship between estimated annual dependable-peaking-capacity benefits and minimum flow at Atlanta, Ga., (Q_A), with and without reregulation, for 1980, 1990, and 2000. Solid line is without reregulation; dashed line is with reregulation; dotted line is benefits with reregulation minus the annualized cost of reregulation.

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