LONG-RANGE PLANNING OF THE OWASA WATER SUPPLY SYSTEM

by

Anthony R. Gagliostro

A report submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements of the degree of Master of Science in Environmental Engineering in the Department of Environmental Science and Engineering, School of Public Health.

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ABSTRACT

The Orange Water and Sewer Authority operates a multiple reservoir system consisting of two primary reservoirs and a third, which is an abandoned portion of a quarry. The authority can increase its long-term water supply by obtaining additional storage capacities at the quarry site or by developing a new source outside the existing watersheds. Mathematical optimization techniques were applied to assist in the long-range planning of the capacity expansion of the reservoir system.

Linear programming models were developed to estimate the safe yield of the system under various conditions. Safe yield functions were derived for different system configurations, inflow conditions, and working volumes. Using projections of future demands, the scheduling of required capacity expansions was identified for different planning alternatives.

A present value cost comparison of the expansion alternatives was performed. The results indicated that substantial savings would be realized by delaying the development of a new source through the expansion of the quarry reservoir.

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1 INTRODUCTION

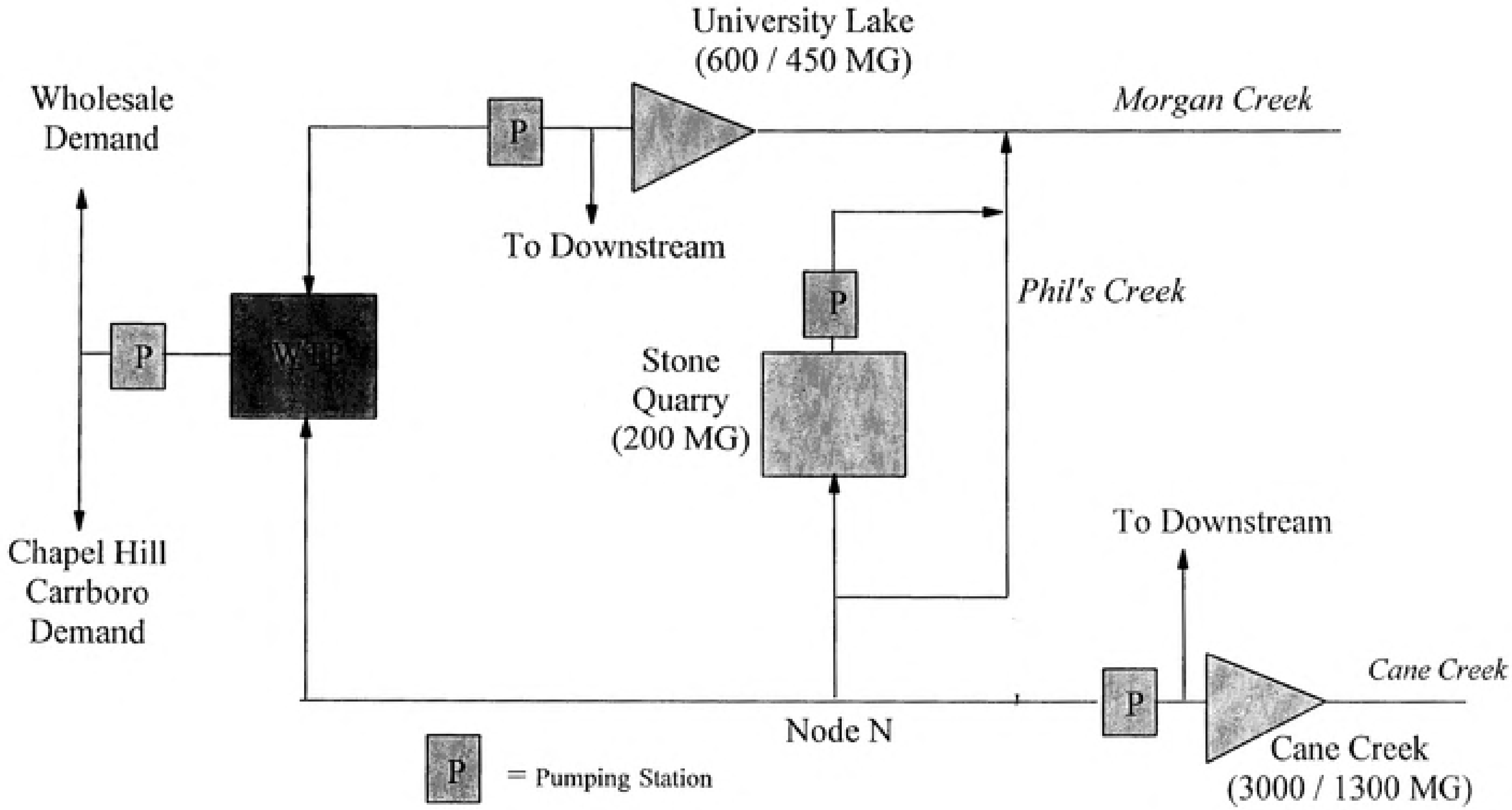
The Orange Water and Sewer Authority (OWASA) provides water and sewer services to the communities of Chapel Hill and Carrboro. The water supply and storage system consists of two reservoirs (University Lake and Cane Creek) in two different watersheds plus a third reservoir with no natural surface supply of its own. The OWASA reservoir system is shown schematically in Figure 1.1.

The University Lake (UL) reservoir is located approximately one mile from the water treatment plant (WTP) in Carrboro, NC. The storage capacity of University Lake is 600 million gallons (MG). Cane Creek (CC) reservoir is located near NC Highway 54 about 11 miles west of the WTP and has a capacity of 3000 MG. The third reservoir, Stone Quarry (SQ), is an abandoned portion of an active quarry site with a capacity of 200 MG. As the quarry site expands in the future, OWASA potentially can acquire easements for increasing storage volumes over time.

The principal reservoirs of the system are University Lake and Cane Creek. As can be seen from Figure 1.1, these are the only reservoirs from which direct releases can be made to meet demands at the WTP. Stone Quarry is currently used only as a backup reservoir for emergency supply.

University Lake and Cane Creek reservoirs each receive natural inflows of surface water from their respective drainage basins. Stone Quarry, on the other hand, does not have a drainage area, and as such, receives no natural inflows. However, water can be pumped from Cane Creek to Stone Quarry, thereby allowing Stone Quarry to augment the storage in the Cane Creek watershed.

Figure 1.1
Schematic of the OWASA Reservoir System



The primary purpose of the reservoir system is water supply. As a result, the major operating constraint on the system is to satisfy the residential and institutional water demands of the Chapel Hill-Carrboro area. Both University Lake and Cane Creek are also used for boating and recreation purposes, limiting the amount by which the reservoirs can be drawn down. Furthermore, as water levels are drawn down, the aesthetic quality of the water deteriorates. The normal operating policy at OWASA is to restrict the maximum water level drawdown to 10 feet at Cane Creek and 12 feet at University Lake, which corresponds to a Cane Creek working volume of about 1300 MG and a University Lake working volume of about 450 MG.

The OWASA reservoir system presently caters to an average water demand of approximately 7.5 million gallons per day (MGD). The Chapel Hill-Carrboro area has experienced considerable development in recent decades, and this trend is expected to continue well into the future. According to one study, water demands are projected to increase at a geometric growth rate of about 2.5 percent per annum [Black & Veatch, 1992]. With such a rapidly growing market, OWASA has recognized that it must plan now for the expansion of its water supply and storage system.

The options available to OWASA for increasing its long-term water supply capacity basically consist of more fully developing the existing sources or developing new sources outside the present watersheds. More specifically, OWASA has two main expansion alternatives under consideration: (1) expanding Stone Quarry; and (2) tapping Jordan Lake (JL). Increased demands can also be met by increasing the working volumes of Cane Creek and University Lake reservoirs. However, this would result in poorer quality water, which will have higher treatment costs associated with it.

OWASA is presently seeking approval from local elected officials of its plan for the Stone Quarry expansion [Easterly, 1994]. Approval of the proposal would allow the American Stone Company to expand its quarry operation, located off NC 54 about 5 miles west of Carrboro, onto 60 acres of OWASA-owned land. The company would excavate about 25 acres of that property. This would keep the quarry in operation until about the year 2030. During that time, excavations of various volumes would be made available to OWASA in stages. It is estimated that once the quarrying was complete, up to 3 billion gallons of total storage would be available at Stone Quarry.

The quarry expansion plan would require approval from the governing bodies of Chapel Hill, Carrboro, and Orange County because the quarry lies in the joint planning area of all three. It is expected to be a hotly debated topic. Many residents of the rural area near the quarry are against the proposal, saying that blasting has already damaged wells and home foundations [Easterly, 1994]. OWASA is pushing for the expansion of Stone Quarry, using the following arguments:

(1) the additional storage would increase water supply capacity,
(2) the additional storage would provide operational flexibility,
(3) the Stone Quarry reservoir would provide storage of higher quality water with little chance of contamination or quality degradation, and,
(4) the better quality water implies reduced treatment costs.

The potential rate of expansion of Stone Quarry is roughly estimated to be 75 MG per year in the form of new excavations. Under the current piping configuration, SQ expansions would serve to augment the storage of the Cane Creek watershed only. On the other hand, if the system was modified to allow Stone Quarry to also receive pumped flows from UL, additional SQ storage would augment storage capacity in both Cane Creek and University Lake watersheds.

OWASA has already taken steps to develop Jordan Lake as a long-term water source. It has received a 10-MGD water allocation from the North Carolina Environmental Management Commission [OWASA, 1993]. This allocation is its share of a 19-MGD, joint allocation to Orange-Alamance Water System Inc., Orange County, Chatham County, and the Town of Hillsborough. OWASA has also purchased approximately 125 acres of land near Jordan Lake. Furthermore, OWASA contracted CH2M HILL in 1991 to conduct an investigation of candidate sites for the raw water intake structure [CH2M HILL, 1991].

Initially, the development plan calls for a raw water pump station to be constructed at the Jordan Lake site, supplying water to University Lake or directly to the existing water treatment plant. Ultimately, a new WTP may be built on the Jordan Lake site. In the consulting engineer's report, a recommendation was made for the location of the intake structure, pipeline corridors, and pump stations. For guidance in project evaluation and implementation, the report also included a preliminary cost estimate for construction of the intake and transmission system based on a single design of the proposed intake system. In addition, a proposed project schedule was presented, indicating that a 5 to 8-year implementation period would be required to complete the project, including construction.

The estimated total capital costs for the proposed water supply and transmission system was given as 19 million dollars (in August 1991 dollars). This is an order of magnitude estimate of the capital costs associated with tapping Jordan Lake. It is expected to be accurate within +50 to -30 percent. This estimate includes construction, engineering, legal and administrative costs. In arriving at this figure, CH2M HILL assumed that intake piping and a structure capable of expansion to 50 MGD would be initially constructed along with a pumping and transmission system delivering 10 MGD to the existing WTP. The Jordan Lake site is more than 15 miles away from the WTP in Carrboro. The total dynamic head based on the proposed 36-inch transmission line would be too large to allow direct pumping to the plant, so two-stage pumping will be required.

Tapping Jordan Lake is a very capital intensive alternative. Of course, OWASA has the option of expanding its existing resources via Stone Quarry, but many issues remain unclear. OWASA is interested in finding out what marginal contribution(s) to long-term water supply would be obtained from additional SQ storage volume(s). The optimal quantity of additional SQ capacity which should be obtained and the timing of its acquisition are also of concern. The other major issues include the assessment of when it will be necessary to tap Jordan Lake and the economic benefits associated with delaying the expensive development of the Jordan Lake source. This report is aimed at helping OWASA address these issues.

The goal of this study is to assist OWASA in planning the capacity expansion of its water supply system. The objectives of this study are as follows:

(1) gain a thorough understanding of the OWASA reservoir system,
(2) assess the potential of further developing the yield from the existing sources via Stone Quarry expansion,
(3) analyze development of the Jordan Lake source with and without Stone Quarry expansion, and,
(4) make recommendations for the Stone Quarry expansion and Jordan Lake development based on the findings.

In order to address the issues and concerns facing OWASA, it is necessary to estimate the long-term water supply capacity of the reservoir system under a variety of conditions. Mainly, these conditions consist of different combinations of working volumes and surface water inflows for the reservoirs. A review of the technical literature indicated that the application of safe yield models would be the best approach to obtaining measures of reliable water supply.

A safe yield can be defined as the maximum quantity of water that can be released from a reservoir or system of reservoirs continuously over the period of time in the streamflow record used in the analysis. Many techniques have been utilized to determine safe yields, but it was clear early on that mathematical optimization models using linear programming was the most appropriate method for this water resources planning situation.

In section 2, the linear programming formulations of the mathematical optimization models developed to determine the safe yield from different configurations of the OWASA reservoir system are presented. This section also includes a background discussion of safe yield models. The safe yield models developed were then applied in the analysis of the long-term water supply from the OWASA system for various conditions. In section 3, a discussion of the estimation of monthly inflow for Cane Creek and University Lake reservoirs is given, which are the major input parameters required in the safe yield models. Then, the safe yield studies that were performed are described and the results from these studies are presented and discussed. With the results from the safe yield models, a present value cost comparison can be conducted to evaluate the expansion alternatives, which is done in section 4. Recommendations are given at the end of section 4.

2 SAFE YIELD MODELS

2.1 BACKGROUND

For a given working volume, reservoir operating policy, and trace of inflows, every reservoir has an associated safe yield. The safe yield of a reservoir is normally defined as the maximum release from the reservoir that can be guaranteed on a sustained basis. However, no yield can be guaranteed with absolute certainty because inflows are stochastic. Safe yields have traditionally been based on historical streamflow records and on the assumption that the sequence will repeat in the future. Some yields may be less than the historical safe yield because inflows in the future may be less than the lowest flows on record.

Although a safe yield cannot be guaranteed with certainty, it can be associated with a probability of exceedance or a measure of its reliability. For a reservoir with a given storage capacity and operating policy, the probability that any particular release will be exceeded can be defined with respect to the probability of exceedance of a certain inflow [Loucks *et al.*, 1981; ReVelle *et al.*, 1969]. These probabilities are normally estimated from unregulated historical streamflows.

A common method used to estimate the probability that any given flow will be exceeded involves the prediction of the mean number of random events that can occur in the future. The probability that such a number of random events occurs is called the mean probability. The mean probability of any particular inflow being equaled or exceeded is based on the assumption that any future flow has an equal probability of falling within any interval defined by a historical streamflow record. If a historical streamflow record consists of n monthly unregulated inflows, then there would be n + 1 streamflow intervals.

Arranging these monthly flows in order and ranking them so that the largest streamflow has the lowest rank, m = 1, and the lowest inflow has the highest rank, m = n, the mean probability that a future monthly inflow will equal or exceed a flow of rank m is m/(n + 1). [Loucks *et al.*, 1981]

To illustrate how the mean probability of inflows relates to the reliability of yields, consider the case that no reservoir exists. Without reservoir storage, the maximum amount of water that can be consistently diverted from the stream (i.e., the safe yield) would be estimated as the lowest flow in the historical streamflow record. The mean probability that this safe yield will be equaled or exceeded is the mean probability of exceedance of the lowest flow, which is n/(n + 1), where n is the number of time periods in the historical record. For example, if the mean probability that the lowest flow will be equaled or exceeded is 0.90, then it can be estimated that, in the future, a release equal to or greater than this low flow can be made 90 percent of the time, which represents the reliability of the safe yield. This illustrates that a safe yield can be defined by the mean probability of that yield being exceeded, which in turn is a function of the total number of periods included in the inflow record.

Reservoir storage makes it possible to increase the safe yield. In periods of high inflow, a volume of water can be stored for release in periods of low inflow. Reservoir storage provides a means of more evenly distributing releases with respect to both time and volume. Assuming an initially empty reservoir, additional increases in storage capacity would permit additional increases in safe yield up to the mean inflow.

Most of the technical literature that refers to safe yields of reservoirs addresses the problem of reservoir design. This problem concerns the determination of the minimum storage capacity of the reservoir required to satisfy a number of purposes, such as water supply, flood control, recreation, and hydroelectric power production [ReVelle *et al.*, 1969]. For the design of a single reservoir dedicated only to water supply, the problem becomes one of determining the minimum storage capacities required to supply various safe yields so that demands can be met. Many different approaches have been suggested for estimating the storage requirements for various safe yields, with the most familiar and successful techniques being conventional mass diagrams [Fair *et al.*, 1966; Loucks *et al.*, 1981], sequent peak [Fair *et al.*, 1966; Thomas and Burden, 1963], simulation [Loucks, 1976; Wurbs and Bergman, 1990], and mathematical programming, especially linear programming [Dorfman, 1962; Loucks *et al.*, 1981; ReVelle *et al.*, 1969; Shih and ReVelle, 1994; Viessman *et al.*, 1975].

In one respect, this report is concerned with the reverse of the reservoir design problem. Estimates of the maximum safe yield that can be obtained from a reservoir or a system of reservoirs with given working volumes, natural inflows, and initial storage conditions are desired. The most appropriate procedure for this situation is linear programming. Linear programming is a powerful optimization technique. Commercial linear programming packages which run quickly and can handle large problems are readily available. Also, there is no inherent nonlinearity in this application because the principal constraints are continuity (or mass balance) equations and reservoir capacity constraints, which are linear functions. In addition, linear programming has the advantage that it easily allows the analysis of multiple reservoir systems.

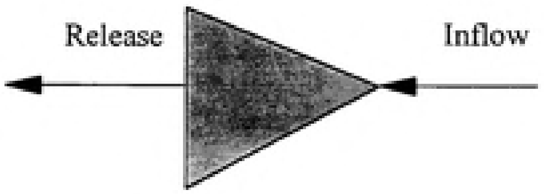
Four different linear programs (LP) were formulated to determine the safe yield corresponding to four different configurations of the OWASA reservoir system: (1) Cane Creek reservoir only, (2) University Lake reservoir only, (3) the existing OWASA reservoir system, and, (4) a modified system that allows Stone Quarry to augment storage capacity of both the CC and UL watersheds. Schematic diagrams of the different arrangements are shown in Figure 2.1.

The first configuration treats Cane Creek as an isolated unit and the second is the same except for University Lake. These configurations were included in the study to determine safe yields for the case where the reservoirs were operated independently. The LP formulation for these two configurations are very similar because they concern only a single reservoir with a certain capacity and a sequence of inflow data. The safe yield models for the independent Cane Creek and University Lake reservoir systems are both described in section 2.2.

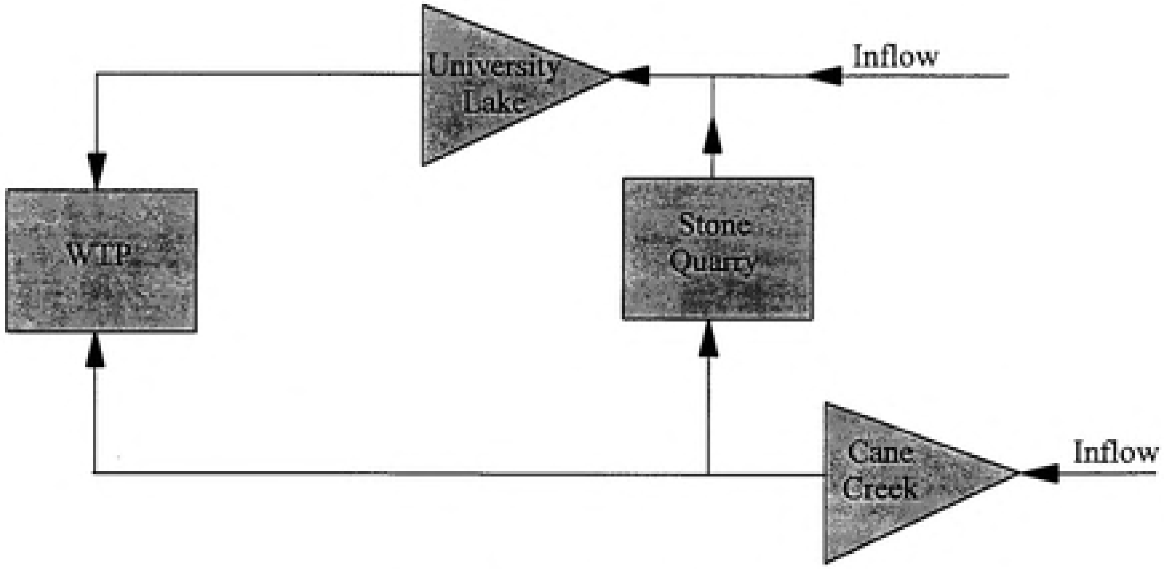
The third configuration considers the existing OWASA reservoir system. Under the current arrangement, shown in Figure 2.1(b), SQ can only receive pumped flows from CC, thereby only augmenting CC reservoir capacity. In the fourth configuration, shown in Figure 2.1(c), the existing system is modified to allow releases from UL to be returned to Stone Quarry for storage. This arrangement, which would involve expensive modification of the existing system, would allow SQ to augment the storage capacity of both the University Lake and Cane Creek watersheds and would likely increase the safe yield of the system. University Lake is much smaller than the Cane Creek reservoir, although the ratio of the UL watershed area to that of Cane Creek is 0.89. The difference in storage capacities is much greater than the differences of inflows between the two basins. Intuitively, additional storage capacity would be most useful in the UL watershed.

The linear program for the fourth configuration is similar to the one developed for the existing OWASA system except that an additional variable must be included to allow for pumping between UL and SQ. The safe yield models for the existing and modified OWASA systems are described in sections 2.3 and 2.4, respectively.

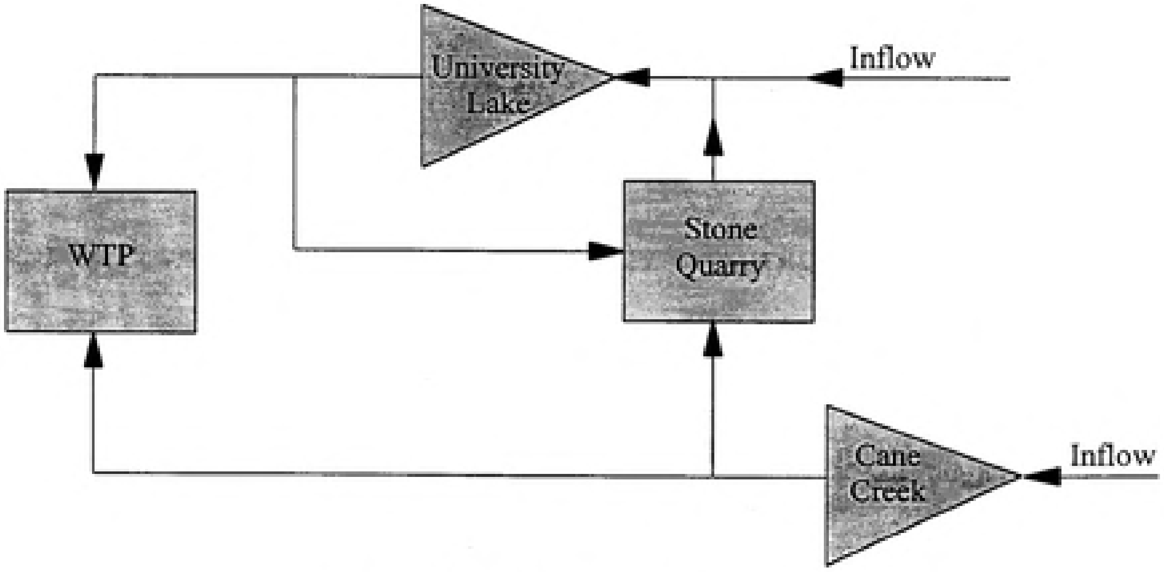
Figure 2.1
Reservoir Configurations



(a) Single Reservoir



(b) Existing OWASA System



(c) Modified OWASA System

2.2 SAFE YIELD MODEL FOR A SINGLE RESERVOIR

Consider a reservoir like the one in Figure 2.1(a) with a given maximum working volume and assume that a historical record of the unregulated monthly streamflows at the site is available for a period of n years. The objective of the model is to find the maximum monthly release that can be sustained over the time period of the analysis (i.e., maximize the monthly safe yield). This is accomplished by manipulating the amount of water that is stored in the reservoir from month to month so that higher monthly releases can be made in periods of low inflow. In certain months, an additional release beyond the safe yield may be necessary in order to maintain the reservoir storage volume within the maximum working volume. These additional releases are termed excess releases. This problem can be readily formulated as a linear program.

Decision Variables

The decision variables to be incorporated in the LP can be defined as follows.

$\mathbf{r}$ = the monthly safe yield

$\mathbf{e}_t$ = the excess release from the reservoir in month t, if any

$\mathbf{s}_t$ = the volume of water stored in the reservoir at the beginning of month t

Parameters

The parameters of the LP consist of a sequence of monthly inflow data, the maximum working volume, and the initial storage volume.

Let

$\mathbf{I}_t$ = the flow into the reservoir in month t

$\mathbf{K}$ = the maximum working volume for the reservoir

$\mathbf{V}$ = the volume of water initially stored in the reservoir (at t =1)

Objective Function

The objective function to be maximized is simply the value of the monthly safe yield.

$$\textbf{Maximize} \quad \mathbf{r}$$

Constraint Equations

The objective function is subject to the following set of linear constraints.

(1) Continuity Constraints

Continuity requires that the storage volume at the beginning of month t, s_t, plus the inflow $\mathbf{I}_t$ less the releases $\mathbf{r}$ and $\mathbf{e}_t$ must equal the storage volume at the beginning of the next month, s_{t+1}. Thus,

$$\mathbf{s}_{t+1} = \mathbf{s}_t + \mathbf{I}_t - \mathbf{r} - \mathbf{e}_t \qquad \text{, for all t.}$$

(2) Reservoir Capacity Constraints

Constraints are required to make sure that the amount of water stored in any period does not exceed the maximum working volume.

$$\mathbf{s}_t \leq \mathbf{K} \qquad \text{, for all t.}$$

(3) Initial Condition

The initial amount of water stored in the reservoir is defined.

$$s_1 = V$$

It should be noted that separate continuity and reservoir capacity constraints are required for each month of reservoir inflow data. For example, if a 14-year historical record of monthly inflow data was used in the model, there would be 168 continuity constraints and 168 reservoir capacity constraints. The total number of constraints would be 337, as would the total number of decision variables.

To obtain the safe yield models for an isolated Cane Creek reservoir and for an isolated University Lake, the parameters incorporated in the above generic model would obviously correspond to the reservoir of interest. That is, the safe yield model for Cane Creek would include inflow data for CC and values for Cane Creek's maximum working volume and its initial storage volume. In the UL safe yield model, the monthly flows into UL would be used, along with values for the maximum working volume and initial storage volume.

2.3 SAFE YIELD MODEL FOR THE EXISTING OWASA SYSTEM

As can be seen from Figure 2.1(b), the demands at the WTP can only be satisfied by releases from Cane Creek and University Lake. The safe yield for the entire OWASA system denotes the maximum amount of water that can be consistently obtained from the system of reservoirs to meet demands. Therefore, the sum of the safe yields from CC and UL to the WTP represents the system safe yield.

Formulations of safe yield models for multi-reservoir systems as linear programs are just extensions of the formulation for a single reservoir. For a system of reservoirs, continuity equations and capacity constraints are written for each reservoir. A description of the LP for the current OWASA system is given below.

Decision Variables

The main decision variables to be determined are the monthly safe yields from CC and UL to the WTP. These releases for any single reservoir are the same for each month, although they would be different for each reservoir. In certain months, excess releases from Cane Creek and University Lake may be required so that the storage volume in these reservoirs does not exceed the corresponding maximum storage capacities. Figure 2.1(b) shows that there are two other routes along which water can be released. Water can be released from CC to Stone Quarry and from Stone Quarry to University Lake. Releases directly from Cane Creek to University Lake are incorporated into these two variables to reduce the required number of decision variables. The volume of water to be stored at the beginning of each month t in each of the reservoirs are also important variables to be decided. The following notation is used for the decision variables.

$\mathbf{r}^{cw}$ = the monthly safe yield from CC to the WTP

$\mathbf{r}^{uw}$ = the monthly safe yield from UL to the WTP

$\mathbf{e}^{c}{}_{t}$ = the excess release from CC in month t

$\mathbf{e}^{u}{}_{t}$ = the excess release from UL in month t

$\mathbf{r}^{cs}{}_{t}$ = the release from CC to SQ in month t

$\mathbf{r}^{su}{}_{t}$ = the release from SQ to UL in month t

$\mathbf{s}^{c}{}_{t}$ = the volume of water stored in CC at the beginning of month t

$\mathbf{s}^{u}{}_{t}$ = the volume of water stored in UL at the beginning of month t

$\mathbf{s}^{s}{}_{t}$ = the volume of water stored in SQ at the beginning of month t

Parameters

The parameters in the model include the working volumes and initial storage volumes for each reservoir, and monthly inflows for both Cane Creek and University Lake.

Let

$\mathbf{I}^c{}_t$ = the inflow to CC in month t
$\mathbf{I}^u{}_t$ = the inflow to UL in month t
$\mathbf{K}^c$ = the maximum working volume for CC
$\mathbf{K}^u$ = the maximum working volume for UL
$\mathbf{K}^s$ = the maximum working volume for SQ
$\mathbf{V}^c$ = the initial CC storage volume
$\mathbf{V}^u$ = the initial UL storage volume
$\mathbf{V}^s$ = the initial SQ storage volume

Objective Function

The objective function to be maximized is the sum of the monthly safe yields from Cane Creek and University Lake, which can be represented as follows.

$$\textbf{Maximize} \quad \mathbf{r}^{cw} + \mathbf{r}^{uw}$$

Constraint Equations

(1) Continuity Constraints

For each month t, mass balance equations must be satisfied at each reservoir site. The change in the stored volume of water must equal the sum of all flows into the reservoir minus all flows out of the reservoir during the time period.

(a) Continuity at Cane Creek

$$\mathbf{s}^{c}_{t+1} = \mathbf{s}^{c}_{t} + \mathbf{I}^{c}_{t} - \mathbf{r}^{cw} - \mathbf{e}^{c}_{t} - \mathbf{r}^{cs}_{t} \quad \text{, for all t}$$

(b) Continuity at University Lake

$$\mathbf{s}^{u}_{t+1} = \mathbf{s}^{u}_{t} + \mathbf{I}^{u}_{t} + \mathbf{r}^{su}_{t} - \mathbf{r}^{uw} - \mathbf{e}^{u}_{t} \quad \text{, for all t}$$

(c) Continuity at Stone Quarry

$$\mathbf{s}^{s}_{t+1} = \mathbf{s}^{s}_{t} + \mathbf{r}^{cs}_{t} - \mathbf{r}^{su}_{t} \quad \text{, for all t}$$

(2) Reservoir Capacity Constraints

The amount of water in storage at the beginning of each month cannot exceed the working volume of the reservoir. Each reservoir requires such a constraint.

(a) Reservoir Capacity Constraint for Cane Creek

$$\mathbf{s}^{c}_{t} \leq \mathbf{K}^{c} \quad \text{, for all t}$$

(b) Reservoir Capacity Constraint for University Lake

$$\mathbf{s}^{u}_{t} \leq \mathbf{K}^{u} \quad \text{, for all t}$$

(c) Reservoir Capacity Constraint for Stone Quarry

$$\mathbf{s}^{s}_{t} \leq \mathbf{K}^{s} \quad \text{, for all t}$$

(3) Initial Conditions

The initial storage volume is defined for each reservoir.

(a) Initial Condition for Cane Creek

$$s^{c}_{1} = V^{c}$$

(b) Initial Condition for University Lake

$$s^{u}_{1} = V^{u}$$

(c) Initial Condition for Stone Quarry

$$s^{s}_{1} = V^{s}$$

This is a much larger LP than the one defined for a single reservoir. Assuming a 14-year record of monthly inflow data for Cane Creek and University Lake, the total number of constraints would be 1011 and the total number of decision variables would be 1178.

2.4 SAFE YIELD MODEL FOR THE MODIFIED OWASA SYSTEM

The modified OWASA system shown in Figure 2.1(c) allows for pumping between University Lake and Stone Quarry. The LP developed in section 2.3 can be revised to characterize this arrangement. New decision variables must be included to denote the release from UL to SQ in each month t.

Let

r^{us}_{t} = the release from UL to SQ in month t.

The continuity equations in section 2.3 for UL and SQ must be rewritten because $\mathbf{r}^{us}{}_t$ represents a flow of water out of University Lake and a flow into Stone Quarry. Thus, the new continuity constraints can be written as follows.

Continuity at University Lake

$$\mathbf{s}^u{}_{t+1} = \mathbf{s}^u{}_t + \mathbf{I}^u{}_t + \mathbf{r}^{su}{}_t - \mathbf{r}^{uw} - \mathbf{e}^u{}_t - \mathbf{r}^{us}{}_t \quad \text{, for all t}$$

Continuity at Stone Quarry

$$\mathbf{s}^s{}_{t+1} = \mathbf{s}^s{}_t + \mathbf{r}^{cs}{}_t + \mathbf{r}^{us}{}_t - \mathbf{r}^{su}{}_t \quad \text{, for all t}$$

All the other constraints and the objective function of section 2.3 remain unchanged.

3 SAFE YIELD ANALYSIS

This section begins with the description of the procedure performed to acquire the monthly inflow data for Cane Creek and University Lake used in the safe yield analysis of the OWASA reservoir system. Then, each of the safe yield studies are discussed in turn, along with the results obtained for each. The primary objective of the safe yield analysis was to assess the extent to which the reliable yield of the existing sources in the OWASA water supply system could be more fully developed via Stone Quarry expansion. The results derived from any investigation are only as meaningful as the data used to arrive at those results. Thus, considerable effort was spent researching and deriving the inflow data required to conduct the analyses so that useful and appropriate results would be obtained.

3.1 RESERVOIR INFLOW DATA

The compilation and estimation of the required unregulated streamflow data is fundamental to any river basin management or planning study. The ideal situation would be to have a gauging station with a long record of historical streamflows immediately upstream from each reservoir that would remain in operation indefinitely. Of course, this is not usually the case. In most situations, the unregulated inflows to each reservoir site and for each period of interest must be estimated based on the measured flows at one or more nearby gauging stations.

The safe yield models require monthly inflow data for Cane Creek and University Lake reservoirs. The best available historical data are from the US Geological Survey (USGS) gauging station on Cane Creek near Teer, NC. This gauging station was located directly upstream from the Cane Creek reservoir, but was in operation only from October

1959 to September 1973, when it was discontinued. This record yields 14 years of historical monthly streamflow data for Cane Creek.

A long historical record of unregulated inflows is not available for University Lake. Values of monthly inflows to UL were estimated based on the Cane Creek inflow value utilized for that period. The Cane Creek and University Lake watersheds are in close proximity to one another and the spatial distribution of monthly rainfall presumably does not vary greatly between them. In this situation, engineers commonly assume the ratio of the drainage areas is equal to the ratio of the inflows [Loucks *et al.*, 1981]. The ratio of the University Lake drainage area to that of Cane Creek is 0.89. Thus, Cane Creek inflow values were multiplied by 0.89 to obtain estimates for University Lake inflows.

The complete record of total monthly streamflows at the "Cane Creek near Teer" gauging station is given in Table 3.1. These data are utilized as one set of reservoir inflow data. That is, one set of inputs to the safe yield models was obtained by using these historical data as monthly inflows to Cane Creek and by estimating University Lake inflows as 89 percent of these values.

It is desirable that the time period of the inflow data used in the safe yield studies encompass periods of drought experienced in the area. There was concern that the 14 years of historical data in Table 3.1 did not cover extreme conditions. A study was undertaken to find a surrogate gauging station with a longer record to use with the models.

Statistical regressions were performed on streamflow data from 15 other gauging stations in the region, including streams in the Cape Fear Basin, the Neuse River Basin, and the Pee Dee River Basin, to obtain a correlation between the "Cane Creek near Teer"

Table 3.1
Historical Monthly Inflows to Cane Creek

	Total Monthly Inflow in Million Gallons per Month (MG/month)											
Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1959										663.40	662.43	733.52
1960	926.11	2744.72	2157.90	1638.95	837.57	225.74	184.25	343.04	196.73	191.62	158.47	206.03
1961	308.01	1798.57	1308.05	1148.43	875.05	1631.45	205.45	303.68	58.36	34.58	71.80	312.15
1962	1852.22	927.40	1237.61	1771.43	253.21	298.19	466.22	312.34	126.67	137.67	1292.38	767.77
1963	828.52	940.97	1998.92	405.21	203.83	112.40	146.26	71.64	66.40	23.73	450.57	353.72
1964	1043.60	1295.65	792.20	1519.58	222.03	96.40	155.76	269.42	190.74	441.73	175.66	648.86
1965	421.37	1294.48	1659.63	447.87	201.96	1101.12	2012.49	430.42	125.05	95.78	90.35	67.86
1966	249.65	1828.30	1205.30	669.54	713.48	153.55	63.66	83.82	170.81	131.06	166.48	322.10
1967	346.27	981.11	357.39	326.37	678.52	151.23	181.67	359.46	130.35	68.44	45.50	747.16
1968	1010.77	263.36	897.54	327.66	246.75	99.20	108.25	23.30	3.56	43.97	254.50	292.18
1969	552.76	844.68	1284.79	654.03	233.56	316.67	75.74	154.07	50.42	402.63	60.10	301.81
1970	248.17	989.44	761.95	798.79	261.74	71.74	40.07	51.70	12.28	16.80	194.53	137.66
1971	354.16	1092.20	924.82	530.59	1235.67	281.13	89.19	162.86	126.67	1805.68	637.87	497.63
1972	655.32	1368.80	420.08	471.13	1154.24	613.96	210.68	96.29	94.36	422.86	1787.98	2278.11
1973	1185.91	2053.85	3819.47	2744.72	747.74	1572.38	462.80	239.77	67.99			

flows and those of an alternative station. A preliminary screening model was used to narrow the choices to a single surrogate gauging station. In this model, yearly discharge values at the "Cane Creek near Teer" site were regressed against the corresponding yearly discharge values at one of the proposed gauging sites. In other words, the explained variable (Y) in this simple regression model was Cane Creek yearly discharges and the explanatory variable (X) was the yearly discharges at a proposed gauging stations. The model can be represented as :

$$Y = \alpha + \beta * X + u$$

where u is the random variable denoting error and α and β are the regression parameters estimated from the data on Y and X.

The yearly discharge values were obtained by summing the recorded daily streamflows at the gauge site, measured in cubic feet per second (cfs), for all days in the water year of interest, where a water year runs from October 1st to September 30th of the next calendar year. Therefore, the units of the yearly discharges are given as cfs-year because the value represents the total flow passing a gauge site each year.

The yearly discharge data used in the preliminary screening analysis are presented in Table 3.2. A summary of the regression results obtained for each of the proposed surrogate gauging stations is given in Table 3.3. Based on the R-squared criterion and t-statistics from the linear regressions of the yearly discharge values, the USGS gauging station which has the closest correlation to "Cane Creek near Teer" is "Flat River at Bahama", which is located in the Neuse River Basin. The R-squared obtained from this regression was 0.90, which was the highest achieved in the preliminary screening analysis. The estimate attained for the coefficient of the explanatory variable, i.e., "Flat River at

Table 3.2
Yearly Discharge Data for Preliminary Screening Model

	Yearly Discharges (cfs-year)							
		CAPE FEAR RIVER BASIN			NEUSE RIVER BASIN			
Water Year	Cane Creek Near Teer	E. Fork Deep Near High Pt.	Black River Near Tomahawk	N. East Cape Fear Near Chinquapin	Flat River At Bahama	Middle Creek Near Clayton ·	Nahunta Swamp Near Shrine	Trent River Near Trent
Oct. '60 - Sept. '61	12678	4765	291413	342626	55040	33195	29274	92102
Oct. '62 - Sept. '63	10790	6625	313296	281454	46120	33672	29829	64050
Oct. '63 - Sept. '64	9924	4650	329034	320616	40260	34770	50142	94062
Oct. '64 - Sept. '65	13865	7540	427488	388692	46848	58926	54900	99186
Oct. '65 - Sept. '66	8343	5234	262788	262788	25523	25181	24815	60756
Oct. '66 - Sept. '67	6394	2656	236639	184586	22790	26657	21827	47818
Oct. '68 - Sept. '69	7361	5580	250423	307153	35583	24920	28980	57789
Oct. '69 - Sept. '70	6190	5394	270054	225155	32024	21858	26491	54280
Oct. '71 - Sept. '72	12418	5922	355016	353824	65643	33356	38133	114783
Oct. '72 - Sept. '73	26898	8794	430952	453572	104010	54853	40386	94105
Drainage Area (square miles)	29	14.8	676	599	149	83.5	80.4	168

	Yearly Discharges (cfs-year)							
	PEE DEE RIVER BASIN							
Water Year	Yadkin River At Patterson	Reedies River at N. Wilksboro	Roaring River Near Roaring	Mitchell River At State Road	LittleYadkin Near Dalton	Hunting Creek at Harmony	Big Bear Near Richfield	Little River Near Star
Oct. '60 - Sept. '61	21203	50051			17611	75044	15932	30268
Oct. '62 - Sept. '63	14713	45750			17970	67344	14275	33196
Oct. '63 - Sept. '64	12920	35099			14384	61122	22363	38430
Oct. '64 - Sept. '65	20752	52704	66612	55266	19325	105042	31586	50142
Oct. '65 - Sept. '66	17175	56364	44286	38796	14420	60390	12151	25657
Oct. '66 - Sept. '67	14843	36635	46593	29514	8066	49599	12749	15484
Oct. '68 - Sept. '69	19977	45514	55780	35907	13391	57941	16410	30722
Oct. '69 - Sept. '70	21471	54138	55262	37444	14093	52878	12762	28598
Oct. '71 - Sept. '72	21451	67303	85924	60610	24168	115715	21320	50991
Oct. '72 - Sept. '73	28583	79439	92765	63887	24062	115986	26083	59789
Drainage Area (square miles)	29	89.2	128	78.8	43	155	56	106

Table 3.3
Preliminary Screening Regression Results

REGRESSION STATISTICS		CAPE FEAR RIVER BASIN			NEUSE RIVER BASIN			
		E. Fork Deep Near High Pt.	Black River Near Tomahawk	N. East Cape Fear Near Chinquapin	Flat River At Bahama	Middle Creek Near Clayton	Nahunta Swamp Near Shrine	Trent River Near Trent
R - squared		0.606	0.676	0.757	0.904	0.638	0.456	0.3503
Number of Observations		10	10	10	10	10	10	10
Constant	estimate	-4525.631	-11170.07	-9363.606	45.4956	-1903.514	2908.003	-474.959
	t - statistic	-0.955	-1.971	-2.1809	0.03125	-0.50502	0.4701	-0.07934
	P - value	0.364	0.0802	0.057087	0.9758	0.6257	0.64947	0.9385
Coefficient	estimate	2.801	0.07154	0.066816	0.241444	0.38544	0.2488013	0.153557
	t - statistic	3.508	4.084	4.9935	8.7059	3.754768	1.4498	2.07698
	P - value	0.007	0.0027	0.00074	1.12E-05	0.0045213	0.181043	0.067596

REGRESSION STATISTICS		PEE DEE RIVER BASIN							
		Yadkin River At Patterson	Reedies River at N. Wilksboro	Roaring River Near Roaring	Mitchell River At State Road	LittleYadkin Near Dalton	Hunting Creek at Harmony	Big Bear Near Richfield	Little River Near Star
R - squared		0.5183	0.5624	0.7034	0.7023	0.59763	0.6349	0.42534	0.67175
Number of Observations		10	10	7	7	10	10	10	10
Constant	estimate	-6919.28	-6213.14	-9184.78	-9101.44	-4278.225	-2582.15	314.828	-1827.98
	t - statistic	-1.0762	-1.0938	-1.4647	-1.4531	-0.90051	-0.65106	0.06502	-0.5238
	P - value	0.3098	0.30247	0.19334	0.1964	0.3913	0.53127	0.949676	0.61306
Coefficient	estimate	0.95321	0.33842	0.3259	0.4517	0.94121	0.18485	0.6018	0.3665
	t - statistic	2.9339	3.2063	3.4434	3.4343	3.44704	3.7298	2.4334	4.40462
	P - value	0.01665	0.01072	0.013744	1.39E-02	0.00731	0.0047	0.03777	0.002901

Bahama" yearly discharges, was 0.241 with a t-statistic of 8.71. This was by far the most significant estimate of the coefficient obtained from the regressions. Also, the regression indicates that the estimate of the constant term (α) for this relationship is not significantly different than zero.

The results from the preliminary screening analysis indicate that "Flat River at Bahama" is a good surrogate gauging station for the "Cane Creek near Teer" site. Records are available for "Flat River at Bahama" from July 1925 to the present. The drainage area above this Flat River gauge site is 149 square miles, which gives a drainage area ratio of Cane Creek to Flat River of 0.19. This ratio is close, but not equal, to the estimate of the coefficient obtained from the regression.

After selection of "Flat River at Bahama" as the most representative gauge site, further statistical analyses were performed to correlate Flat River flows with Cane Creek inflows on a monthly basis. The data consisted of monthly discharges at the two gauging stations for the overlapping time period of the historical records. The monthly discharges were calculated by summing the recorded daily streamflows, reported in cfs, for all the days in that month. The units of the resulting total monthly flows are cubic feet per second-month (cfs-month).

Linear regressions using dummy explanatory variables were performed to evaluate the seasonal relationships between Flat River and Cane Creek data. That is, dummy variables were included in the regression analysis to assess variations in the relationship in dry months versus wet months. The regression model used in the analysis can be expressed as :

$$CC = b_o + b_1{*}DUMMY1 + b_2{*}FR + b_3{*}DUMMY2 + u$$

where CC and FR are the total monthly flows at Cane Creek and at Flat River in cfs-month; b_0, b_1, b_2, and b_3 are the regression parameters; u is the error term, and DUMMY1 and DUMMY2 represent the dummy explanatory variables. The dummy variables were defined as follows.

$$\text{DUMMY1} = \begin{cases} 0 & \text{for wet months of January-July, November, and December} \\ 1 & \text{for dry months of August, September, and October} \end{cases}$$

$$\text{DUMMY2} = \begin{cases} 0 & \text{for wet months of January-July, November, and December} \\ \text{FR} & \text{for dry months of August, September, and October} \end{cases}$$

The use of the dummy variables allows the joint estimation of the two seasonal relationships. When the regression model is run, the estimated equation for the wet season would be:

$$CC = \bar{b}_0 + \bar{b}_2 * FR$$

and the estimated equation for the dry season would be:

$$CC = (\bar{b}_0 + \bar{b}_1) + (\bar{b}_2 + \bar{b}_3) * FR$$

where $\bar{b}_0$, $\bar{b}_1$, $\bar{b}_2$, and $\bar{b}_3$ are the estimated parameters. In the regression model above, the coefficient of the variable DUMMY1, b_1, measures the difference in the constant term for the dry season relationship from that of the wet season relationship. The coefficient of the DUMMY2 variable, b_3, measures the difference in the slope coefficient for the dry season equation from that for the wet season equation. The constant and the slope coefficient of the wet season equation are b_0 and b_1, respectively. In this case, the wet months were taken as the base group and the coefficients of the dummy variables measure the changes in the parameters of the dry season equation with respect to the parameters of wet season equation. The benefit of the use of dummy variables versus estimating the model separately for each season is that statistical inferences about the differences between seasonal equations can be made by testing the significance of the coefficients of the dummies [Maddala, 1992].

Many analyses were conducted to determine the best seasonal relationships by including different months in the dry month category. The highest correlation between the monthly flows at Cane Creek and Flat River, based on the highest adjusted R-squared, was obtained by defining the dry season of each year as the months of August, September, and October, with all other months comprising the wet season. The results of the regression analyses for this arrangement are given in Appendix A. In the initial analysis, the full regression model was used. Monthly Cane Creek inflows were regressed against a constant, a dummy variable measuring the shift in the constant term between dry and wet seasons, monthly Flat River inflows, and another dummy variable measuring the change in the slope coefficient (i.e., the coefficient on the variable representing the monthly Flat River inflows) in the dry season equation with respect to that of the wet season equation. The results indicated that neither the constant nor the coefficient of DUMMY1 was significantly different than zero at the 5 percent significance level. On the other hand, the coefficients of the variables FR and DUMMY2 were highly significant.

In the process of simplifying a regression model, the order in which insignificant variables are dropped from the model can influence the final model. The typical procedure for model simplification consists of dropping insignificant variables in a stepwise fashion and analyzing all permutations of the order in which insignificant variables can be dropped. In this case, the next analysis involved dropping the constant from the full model and the results from the regression indicated that the coefficient of DUMMY1 was again insignificant. Then, the variable DUMMY1 was dropped from the full model, with the constant term included, and the constant term was found to insignificant. These regressions revealed that the constant term was not found to be significant for the dry or wet season and that both the constant term for the wet season and the dummy variable measuring the shift in the constant term in the dry season can be dropped from the full model.

The final regression analysis consisted of regressing the Cane Creek monthly inflows against the Flat River inflows and a dummy variable measuring the shift in the slope coefficient between the seasons. Both regression coefficients were found to be highly significant. This indicated that two seasonal models were required to describe the correlation between Flat River and Cane Creek data. The coefficient of the FR variable given in Appendix A for this regression is the estimated slope coefficient for the wet season relationship. The estimated slope coefficient in the equation for the dry season is the sum of the coefficients of the DUMMY2 and FR variables estimated by the regression. The final relationships are given below:

$$CC = 0.245 * FR \qquad \text{for the wet months of November-July}$$

$$CC = 0.116 * FR \qquad \text{for the dry months of August-October}$$

where CC and FR are the total monthly flows at Cane Creek and at Flat River in cubic feet per second-month, respectively.

The above models were used to produce surrogate monthly inflows to Cane Creek for the past 33 years. In other words, each monthly streamflow value in the record for the "Flat River at Bahama" gauging station during the time period from October 1959 to

September 1992 was entered into the appropriate equation above to obtain an estimate of the corresponding inflow to Cane Creek. These surrogate CC inflows were then multiplied by 0.89, as done with the historical set of inflows, to obtain monthly inflows to University Lake. The surrogate monthly inflow data for Cane Creek obtained from this procedure are reported in Table 3.4. The actual historical Flat River at Bahama streamflows, in million gallons per month, are given in Table A.1 of Appendix A.

The safe yield models, especially the ones for the entire reservoir system would become rather large and cumbersome if 33 years of monthly reservoir inflow data were used, and solution on a personal computer would be difficult. Furthermore, the reliability of the safe yield estimates only increases marginally by using 33 years as opposed to a shorter record, say, the 14 years of historical monthly inflow data from the CC gauging station at Teer. There are 396 monthly periods in 33 years and the estimated reliability of safe yield values obtained from models using such a length of inflow data would be about 99.75 percent (i.e., 396/(396+1)). On the other hand, using the 168 monthly inflow values contained in 14 years, the reliability of the safe yield would be estimated as 99.4 percent. It is much more important that the inflow records include drought conditions than that the length of the records be long.

In order to keep the linear programs for the safe yield analysis to a manageable size while extending the analysis period to include more severe drought conditions, the 33-year sequence of surrogate reservoir inflows was divided into four different sets. Each set consists of fourteen consecutive years of data. The sets overlap one another by 5-year intervals. The reason 14 years was taken as the length for these sets of surrogate inflows was to maintain consistency with the historical set of inflow data.

Table 3.4
Surrogate Monthly Inflows to Cane Creek

Year	Total Monthly Inflow in Million Gallons per Month (MG/month)											
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1959										521.47	940.24	1190.91
1960	1112.27	3059.81	2085.01	1684.50	908.52	185.35	183.46	241.73	257.28	115.31	156.18	253.69
1961	54.54	1862.71	1338.69	1316.96	887.28	578.57	452.84	445.98	72.19	33.86	82.45	789.45
1962	3112.29	2039.50	1733.49	1894.27	264.31	576.03	32.82	236.70	66.25	30.09	1364.69	694.00
1963	910.59	876.97	2373.42	337.41	214.84	97.83	122.56	91.22	27.95	14.02	623.66	444.75
1964	1288.58	1521.03	850.18	786.59	159.67	139.53	161.08	79.06	111.78	271.67	208.03	586.50
1965	539.41	1460.62	1540.21	871.26	257.81	418.75	647.38	112.68	29.51	30.97	52.28	38.72
1966	158.60	1651.52	1153.33	192.49	493.11	106.53	25.35	116.28	79.51	61.30	95.13	300.62
1967	480.90	882.84	355.80	239.42	167.28	545.38	279.85	43.60	21.27	15.53	35.42	930.56
1968	1201.85	298.56	1101.65	355.16	875.54	182.81	138.10	15.89	1.60	4.98	139.54	268.86
1969	599.82	856.52	1642.32	1044.41	249.73	442.37	142.07	69.19	47.30	59.22	53.51	386.40
1970	243.22	970.84	664.35	983.52	433.17	170.45	868.08	73.19	10.82	14.46	542.42	262.09
1971	593.16	1498.51	1050.59	792.14	1165.86	247.03	141.43	275.01	629.57	1306.62	994.78	654.04
1972	496.12	1629.16	502.46	852.55	955.62	905.51	265.42	66.13	120.73	746.68	1928.04	2069.79
1973	1193.13	2116.24	2399.58	2241.66	621.70	629.47	464.41	549.57	43.27	20.42	61.17	1035.53
1974	1726.20	1277.17	938.33	687.18	905.35	223.88	86.73	279.07	1041.15	68.43	150.15	661.49
1975	2852.89	1364.21	4387.40	637.71	563.35	205.33	3922.35	110.05	351.86	98.48	293.01	391.95
1976	1151.11	664.03	411.29	271.29	149.52	127.67	45.06	9.41	5.84	65.14	117.00	518.79
1977	607.59	300.46	1033.62	312.83	139.37	51.61	47.49	6.82	20.05	47.19	235.69	626.93
1978	3077.25	411.93	1505.96	2270.36	2818.49	260.35	625.98	245.93	64.05	15.85	73.90	622.97
1979	2219.30	2972.13	1684.65	841.30	793.10	620.90	154.12	91.01	353.97	167.67	1466.64	370.54
1980	1202.01	580.16	1585.72	983.20	574.92	357.23	118.19	18.91	42.23	40.10	154.54	121.14
1981	97.35	537.50	404.00	286.35	110.04	137.53	706.06	133.38	82.86	173.97	90.22	693.21
1982	1745.86	1704.32	1209.78	434.28	259.08	1756.00	398.45	504.72	34.33	337.20	281.91	1257.35
1983	815.13	1910.91	2911.56	2794.54	959.10	364.52	123.86	13.21	5.20	14.40	243.21	1412.41
1984	1411.15	2243.09	2928.05	2185.22	739.98	298.08	1171.57	123.72	26.95	37.59	78.96	360.87
1985	1021.42	1686.40	359.29	169.97	155.23	62.34	117.09	277.51	40.38	52.73	2328.07	764.71
1986	309.03	395.28	929.30	248.77	134.61	37.34	39.86	303.19	20.35	14.13	124.31	916.23
1987	1535.30	1878.73	2581.76	1433.66	358.81	268.28	285.34	12.44	45.68	28.62	154.12	499.45
1988	865.71	627.88	383.86	443.80	210.24	72.78	26.07	29.75	32.45	77.07	642.15	195.50
1989	340.58	2221.37	3248.81	1536.40	1484.08	468.06	1094.03	210.93	90.59	277.19	380.06	937.06
1990	1350.89	1698.13	770.58	1289.06	1208.19	313.94	76.58	29.30	5.41	352.39	280.96	689.08
1991	2017.15	331.54	1547.98	576.67	247.03	61.17	22.55	15.17	45.06	46.17	31.39	155.91
1992	1501.84	619.64	1015.39	709.85	156.34	148.57	145.71	62.98	26.88			

In all, five different sets of monthly reservoir inflows were used to make the safe yield analyses, each 14 years long. The sets can be defined with respect to how the Cane Creek inflow values included in the set were derived and the time period covered in the data set. For each data set, the University Lake monthly inflows were estimated as 89 percent of the Cane Creek monthly inflows. The first set, denoted Set 1A, consists of the historical streamflow trace at Cane Creek for the period from October 1959 to September 1973. The second set, Set 1B, covers the same time period as Set 1A but is comprised of the surrogate CC inflows obtained for that period. The next three sets consist of portions of the surrogate inflows. The following summarizes the source (i.e., historical or surrogate) of the monthly Cane Creek inflows and the time period incorporated in each of the data sets.

Set	Description
1A	Historical for the period from October 1959 to September 1973
1B	Surrogate for the period from October 1959 to September 1973
2	Surrogate for the period from October 1965 to September 1979
3	Surrogate for the period from October 1970 to September 1984
4	Surrogate for the period from October 1975 to September 1989

3.2 CANE CREEK SAFE YIELD ANALYSIS

The first safe yield study considered Cane Creek reservoir as an isolated system. The objective of this investigation was to obtain estimates of the reliable yield from the reservoir for various working volumes and inflow conditions assuming that Cane Creek reservoir was operated as an independent unit. That is, the only allowable releases from Cane Creek were to the water treatment plant in order to meet demands. Releases to University Lake and Stone Quarry were not permitted.

The formulation of a safe yield model for this single reservoir configuration was described in section 2.2. Each of the Cane Creek monthly streamflow traces associated with the five sets of inflow data discussed in the previous section were incorporated in separate safe yield models according to the formulation of section 2.2. Then, the models were solved for various values of the working volume of the reservoir. All the safe yield analyses discussed in this report were conducted on a personal computer using the linear programming solver software XA.

The results from these models are presented in Table 3.5, where the safe yields from the isolated Cane Creek system are given in million gallons per day. To obtain these values, the optimal monthly safe yield values were divided by 30 to give an average daily safe yield. The safe yield values were converted because releases and demands are normally considered on a daily rather than monthly basis. Each of the safe yield values in the table have the same estimated reliability, or probability of exceedance, because each was derived based on a 14-year trace of monthly inflow data. As discussed in section 2.1, this reliability can be estimated as n/(n+1), where n equals the number of monthly periods in the inflow data sequence. Using a 14-year sequence of monthly inflow data, the reliability of the safe yield is estimated to be approximately 0.994. That is, it is predicted that the reservoir will fail to provide a release equal to or greater than the given safe yield values less than one percent of the time.

Trial working volumes greater than the maximum storage capacity of the Cane Creek reservoir, which is 3000 MG, were included in the analysis to investigate the potential of more fully developing the yield from the CC watershed by augmenting the storage in that watershed, either via Stone Quarry or otherwise. The "Initial Storage Volume" column in Table 3.5 refers to the initial condition included in the models. A

Table 3.5
Cane Creek Safe Yield Study Results

Notes :

Set 1A - Historical Inflow Data from October 1959 to September 1973

Set 1B - Surrogate Inflow Data from October 1959 to September 1973

Set 2 - Surrogate Inflow Data from October 1965 to September 1979

Set 3 - Surrogate Inflow Data from October 1970 to September 1984

Set 4 - Surrogate Inflow Data from October 1975 to September 1989

Working Volume (MG)	Initial Storage Volume (MG)	Safe Yield (MGD)				
		Set 1A	Set 1B	Set 2	Set 3	Set 4
0	0	0.12	0.05	0.05	0.17	0.17
100	100	1.84	1.36	1.36	1.48	1.48
500	500	4.62	5.09	4.49	4.49	4.49
700	700	5.83	6.24	5.63	5.63	5.63
1000	1000	7.26	7.90	7.24	7.24	7.24
1300	1300	8.69	9.54	8.66	8.66	8.66
1500	1500	9.53	9.91	9.35	9.35	9.35
2000	2000	11.61	10.84	10.19	10.19	10.19
2500	2500	12.15	11.73	11.02	11.02	11.02
3000	3000	12.44	12.56	11.85	11.85	11.85
3500	3000	12.74	13.40	12.69	12.69	12.69
4000	3000	13.04	14.01	13.52	13.52	12.98
5000	3000	13.63	14.85	13.62	14.98	12.98
10000	3000	16.61	17.20	13.62	20.93	12.98
20000	3000	18.47	19.26	13.62	24.25	12.98

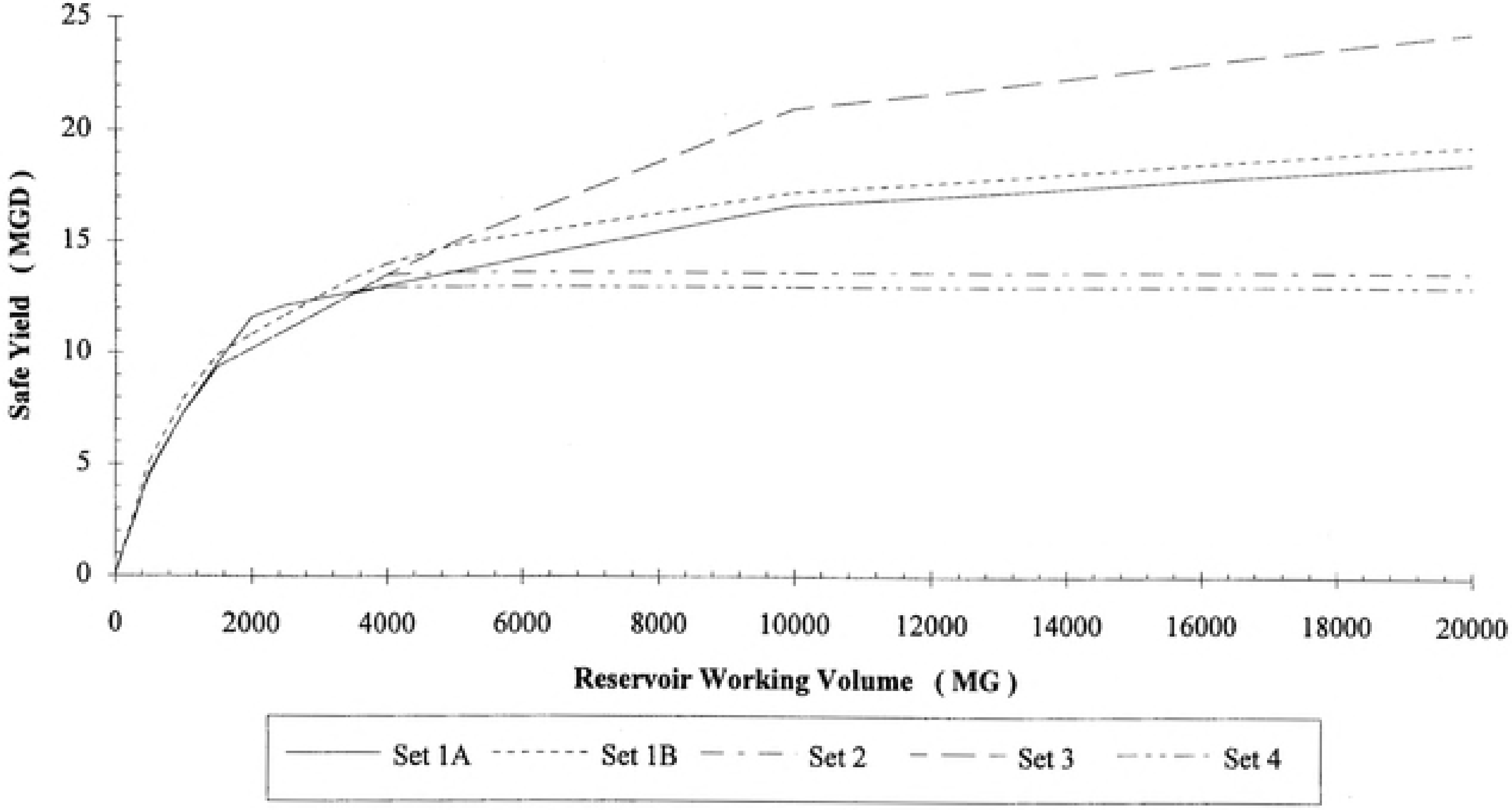
systematic procedure was used to set the volume of water initially stored in the reservoir. For trial working volumes less than the maximum existing storage capacity of the reservoir (3000 MG in the case of Cane Creek), the initial storage volume was set equal to the trial working volume. For trial working volumes greater than the maximum existing storage capacity, the initial storage volume was set equal to the maximum capacity. This procedure was also employed in each of the other studies.

From Table 3.5, it can be noted that at a Cane Creek working volume of, say, 700 MG and with the historical inflow data set (Set 1A), the safe yield from the reservoir is approximately 5.8 MGD. For the presently used Cane Creek working volume of 1300 MG, the model incorporating the historical inflows estimated the safe yield to be about 8.7 MGD. At the maximum storage capacity of 3000 MG, the safe yield is approximately 12.4 MGD, but to obtain this yield, it would be necessary to allow the water level in the reservoir to fluctuate from completely full to empty, which is undesirable due to water quality and recreational concerns. It is important to stress that these estimates of the reliable yield from the CC watershed apply only to the case in which the reservoir is operated as an isolated system.

A graphical representation of the results is given in Figure 3.1, which shows the safe yield from the isolated Cane Creek reservoir system, in MGD, as a function of the CC working volume. These safe yield functions define the maximum constant release that could be sustained over the period of the given series of inflows as a function of reservoir working volumes. Each of the five curves in the figure represent the results from a safe yield model utilizing one of the 14-year sets of monthly inflow data.

The curves in Figure 3.1 illustrate the typical characteristics of safe yield functions [Loucks *et al.*, 1981]. They are concave functions which reach or approach a maximum

Figure 3.1
Safe Yield for Isolated Cane Creek Reservoir
with Different 14-year Sets of Inflow Data

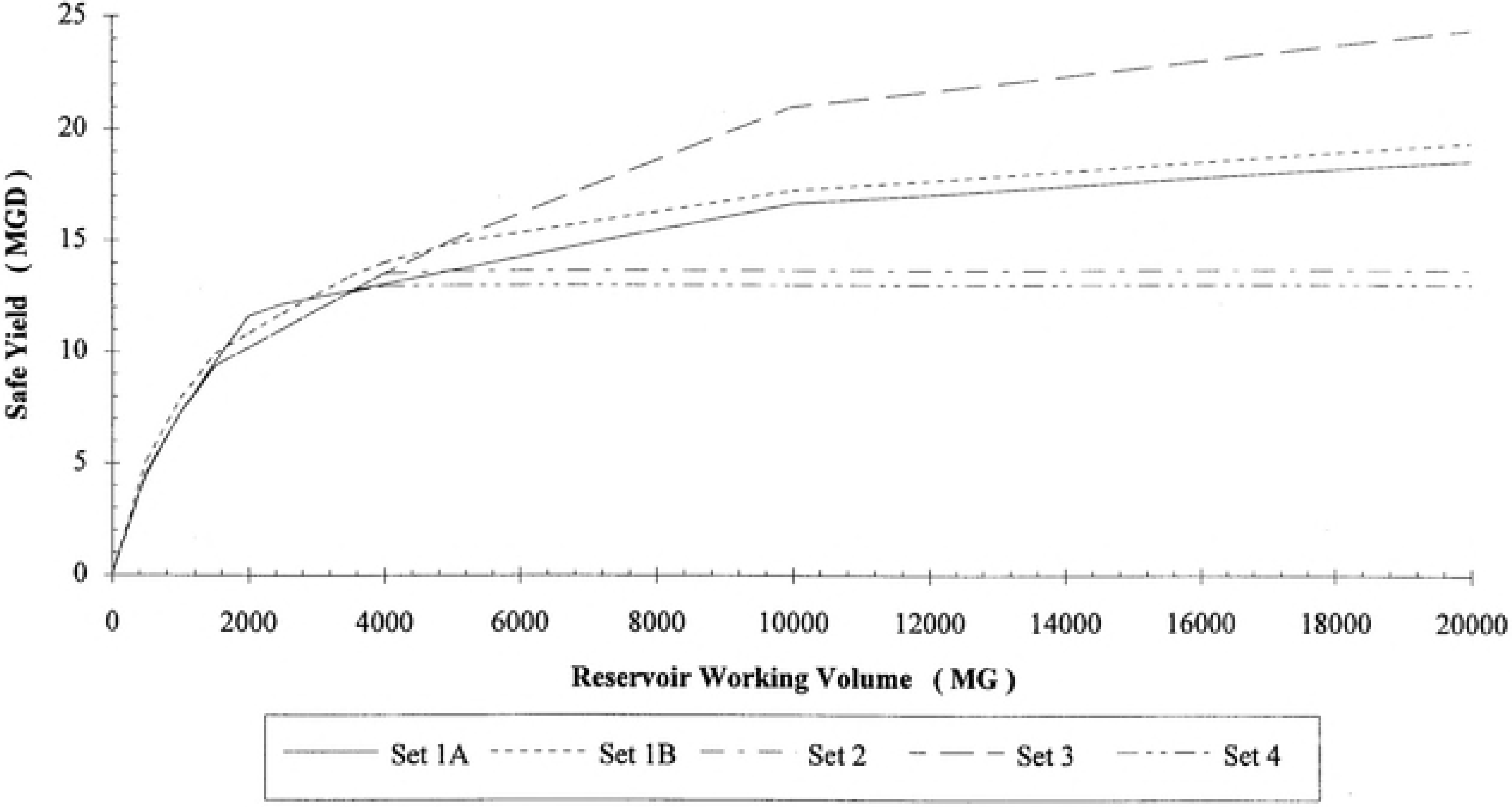


safe yield value with increasing working volumes. From the decreasing slopes of the curves, it can be noted that the marginal increase in safe yield diminishes as the working volume increases. In other words, additional increases in working volume give smaller and smaller increases in the reliable yield from the reservoir.

Figure 3.1 also illustrates the sensitivity of the safe yield from the isolated Cane Creek reservoir with respect to the different sets of inflow data. The safe yield curves do not vary greatly for the lower working volumes, especially for working volumes less than 2000 MG. With the currently utilized storage capacity at Cane Creek restricted to a maximum of 1300 MG, this implies that the yields that presently would be obtained from an isolated Cane Creek reservoir are insensitive to inflow conditions represented by the different data sets. This is most likely because the working volumes are restricted to the extent that, for each of the inflow data sets, the flows into Cane Creek are sufficient to maintain the reservoir close to full, especially considering that the reservoir is initially assumed to be full. Thus, the same volume of water would be available to be distributed over critical periods in each of the inflow data sets, resulting in similar values of the safe yield for a given working volume.

In addition, the results indicate that most of the safe yield values for Sets 2, 3, and 4 are the same for working volumes less than 4000 MG. This is due to the fact that a critical drought period is common to all three of these inflow data sets. An extended drought occurred during the years of 1976 and 1977, and this period is covered by the overlapping interval of the three data sets, which is from October 1975 to September 1979. Assuming the inflows were sufficient to fill the reservoir just before the beginning of the drought, the yield that could be sustained over this common critical period would have to be equal because the duration of the critical period, the inflows during that period, and the storage volume just prior to the beginning of that period would all be the same.

Figure 3.1
Safe Yield for Isolated Cane Creek Reservoir
with Different 14-year Sets of Inflow Data



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Although the safe yield curves are similar for the lower range of trial working volumes, they begin to diverge for working volumes greater than 5000 MG. This implies that the potential for further developing the flow from the Cane Creek watershed through increasing storage capacities depends of the inflow conditions. However, considering the most conservative safe yield function, given by Set 4, it would be possible to increase the reliable yield from an isolated CC reservoir from about 8.7 to 13 MGD by increasing the working volume from the presently used value of 1300 MG to about 4000 MG.

A comparison of the results from the historical inflow data (Set 1A) and the surrogate inflow set covering the same time period (Set 1B) characterizes how well the surrogate inflows predict the actual safe yield from the isolated Cane Creek reservoir. The similarity in the safe yield functions obtained from these two inflow data sets indicates that using the surrogate inflows to predict the safe yield from the reservoir for the other time periods is reasonable. This implies that the surrogate inflows based on Flat River measurements are effective in estimating the reliable yield for periods not covered by the historical record.

3.3 UNIVERSITY LAKE SAFE YIELD ANALYSIS

The safe yield analysis for the isolated University Lake reservoir system was very similar to that for the Cane Creek system. In this case, University Lake was considered as an independent unit and the only flows into the reservoir were the natural inflows from the watershed. Releases from Stone Quarry or Cane Creek to University Lake were not considered. The traces of University Lake monthly inflows included in Sets 1A, 1B, 2, 3, and 4 were used as input to the LP formulation of the safe yield model for a single reservoir, as given in section 2.2. The models were then solved for various trial values of the working volume of the University Lake reservoir. Trial working volumes greater than the total volume of the reservoir, which is 600 MG, were included to analyze the possibility of increasing the water supply from University Lake through increasing its storage capacity. The results from this analysis are given in Table 3.6 and Figure 3.2.

According to the model using the historical inflow data (Set 1A), the reliable yield from an isolated University Lake reservoir is estimated to be about 2.5 MGD for a working volume of 200 MG. A yield of approximately 4.1 MGD is estimated to be obtainable with the normal working volume of 450 MG. Utilizing the maximum storage capacity of 600 MG, the safe yield is about 5.1 MGD, but as before, this implies that the reservoir varies from completely full to empty.

From the results given in Table 3.5 and Table 3.6 for Set 1A, it can be noted that if the University Lake and Cane Creek reservoirs were operated independently at their normal working volumes of 450 MG and 1300 MG, respectively, a total safe yield of about 12.8 MGD would be obtainable from the system. In section 3.4.4, this value is compared to the reliable yield from the system if the two reservoirs were jointly operated.

The safe yield curves shown in Figure 3.2 follow similar trends to those obtained in the Cane Creek analysis. Each of the curves indicates diminishing returns to safe yield with increasing UL working volumes. For University Lake working volumes less than 1000 MG, the safe yields for the five inflow data sets are all nearly the same. For this range of working volumes, the available working volume and the initial storage volume are the dominant factors determining the safe yield, while the variation in the inflows between the data sets is not critical. Also, as can be seen from Table 3.6, the values of the safe yield for Sets 2, 3, and 4 are exactly equal for most of the working volumes less than

Table 3.6
University Lake Safe Yield Study Results

Notes :

Set 1A - Historical Inflow Data from October 1959 to September 1973

Set 1B - Surrogate Inflow Data from October 1959 to September 1973

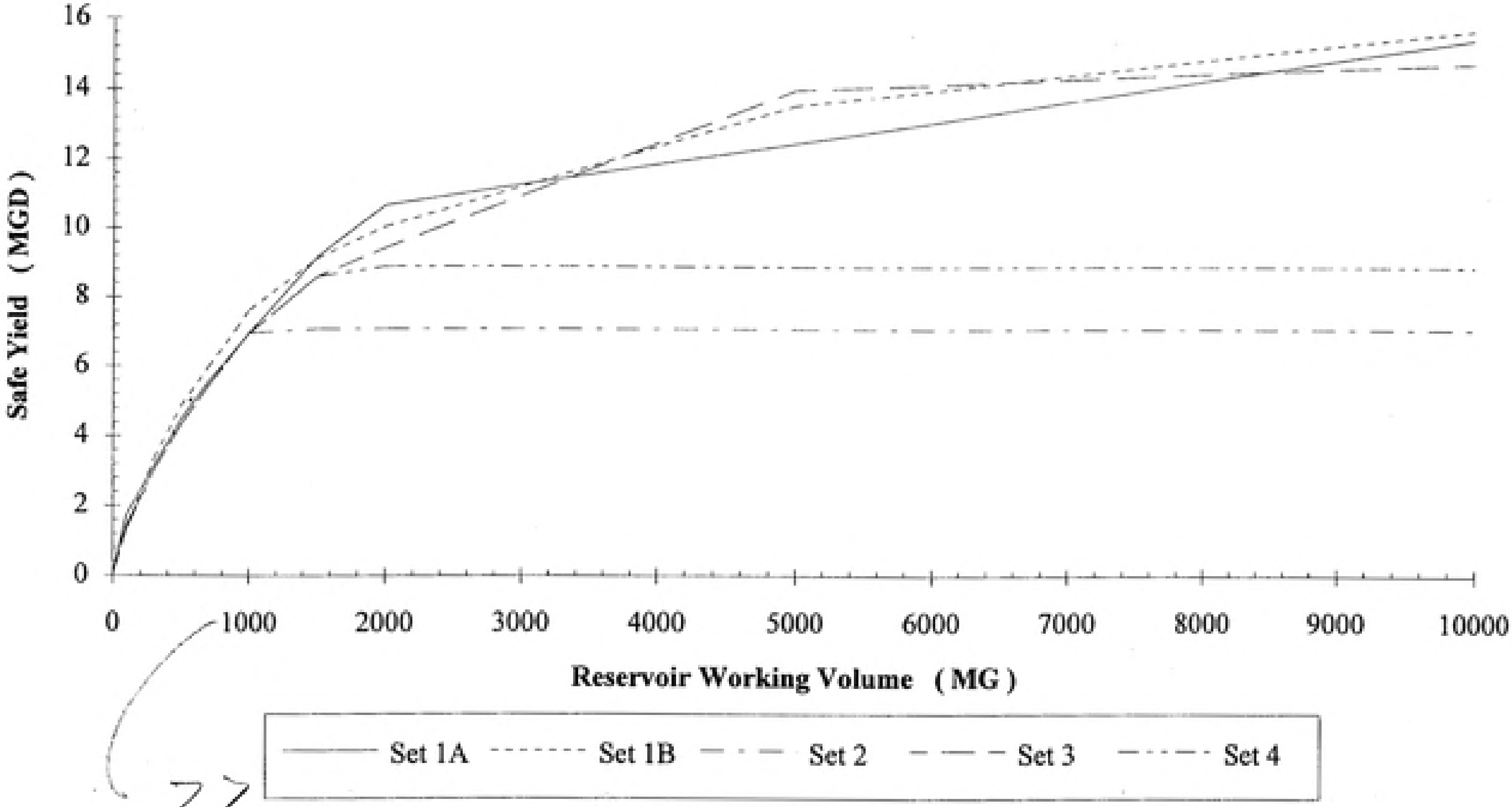
Set 2 - Surrogate Inflow Data from October 1965 to September 1979

Set 3 - Surrogate Inflow Data from October 1970 to September 1984

Set 4 - Surrogate Inflow Data from October 1975 to September 1989

Working Volume (MG)	Initial Storage Volume (MG)	Safe Yield (MGD)				
		Set 1A	Set 1B	Set 2	Set 3	Set 4
0	0	0.11	0.05	0.05	0.15	0.15
100	100	1.73	1.33	1.33	1.44	1.44
200	200	2.48	2.44	2.36	2.36	2.36
300	300	3.14	3.36	3.03	3.03	3.03
400	400	3.81	4.19	3.69	3.69	3.69
450	450	4.14	4.57	4.03	4.03	4.03
500	500	4.48	4.87	4.32	4.32	4.32
600	600	5.08	5.42	4.88	4.88	4.88
700	600	5.56	5.98	5.43	5.43	5.43
800	600	6.03	6.53	5.99	5.99	5.99
900	600	6.51	7.09	6.49	6.49	6.49
1000	600	6.99	7.65	6.96	6.96	6.96
1500	600	9.17	9.13	7.08	8.60	8.60
2000	600	10.68	10.05	7.08	9.43	8.90
5000	600	12.46	13.55	7.08	13.99	8.90
10000	600	15.44	15.70	7.08	14.77	8.90

Figure 3.2
Safe Yield for Isolated University Lake Reservoir with Different 14-year Sets of Inflow Data



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Total Vol = 600 MG

1000 MG, which again indicates that a critical drought period is common to each of these inflow data sets.

The safe yield curves diverge for working volumes greater than 1000 MG. As expected, the working volume required to fully develop the water supply from the University Lake watershed and the maximum safe yield that can be obtained from the system depends on the trace of inflow data. However, each of the safe yield functions in the figure suggests that there is potential for increasing the yield from the UL watershed via additional storage capacity. It can be stated conservatively that increasing the working volume of University Lake from its present value of 450 MG to 1500 MG would increase the reliable yield from about 4 MGD to 7 MGD if the reservoir was operated as an isolated unit.

3.4 SAFE YIELD ANALYSIS OF THE EXISTING OWASA SYSTEM

This section describes the study conducted to evaluate the relationship between the reliable yield from the entire OWASA reservoir system as it presently exists and the working volumes of the reservoirs. The main emphasis of the analysis was to determine how expansion of the Stone Quarry reservoir would affect the sustainable yield from the entire system (given the unlikelihood of expanding either University Lake or Cane Creek). The LP model in section 2.3 was employed for this investigation. Incorporating each of the five inflow data sets into this LP formulation produced five different safe yield models.

This analysis of the existing OWASA system consisted of four stages. First, the results from the models utilizing Sets 1A and 1B were compared to assess how useful the surrogate Flat River inflows were in predicting the safe yield from the entire reservoir system for inflow conditions different than the historical data available. Second, in order to investigate the sensitivity of the reliable yield from the system to inflow conditions, the safe yield models using Sets 1A, 2, 3, and 4 were solved for various Stone Quarry working volumes, while the working volumes of Cane Creek and University Lake were fixed at their maximum storage values (600 MG for UL and 3000 MG for CC). The third stage consisted of conducting an analysis of the sensitivity of the safe yield function for an expanding Stone Quarry to various combinations of UL and CC working volumes. Finally, the safe yield function was derived for the important case that considered the expansion of the currently defined OWASA system via Stone Quarry (i.e., expand SQ with the present UL and CC working volumes of 450 MG and 1300 MG, respectively).

3.4.1 Comparison of Historical and Surrogate Inflow Results

Table 3.7 presents the results from the safe yield models using inflow data from Set 1A and Set 1B. The working volumes of Cane Creek and University Lake were held constant at 3000 MG and 600 MG, respectively. The safe yield models were then solved for increasing Stone Quarry working volumes. Trial SQ working volumes were selected so as to encompass all expansion possibilities. The trial working volumes were initially increased at 50 MG, then 100 MG, and finally at 200 MG intervals. With the approval of OWASA's proposal for the expansion of Stone Quarry, as discussed in section 1, up to 3000 MG of storage may eventually be available at the quarry site. However, with the quarry operation restricted to the current property boundaries, the maximum excavation is expected to be about 1000 MG.

The current working volume of Stone Quarry is 200 MG. Following the procedure in section 3.2, the initial storage volume of Stone Quarry was set equal to the trial working volume if the working volume was less than 200 MG; for working volumes greater than 200 MG, the initial storage volume was set at 200 MG.

Table 3.7
Existing System Safe Yield Study Results
Comparison of Results using Historical and Surrogate Inflow Data

Notes :

Set 1A - Historical Inflow Data from October 1959 to September 1973

Set 1B - Surrogate Inflow Data from October 1959 to September 1973

Cane Creek Storage Capacity fixed at 3000 MG

University Lake Storage Capacity fixed at 600 MG

Initial Conditions : Initial Cane Creek Storage = 3000 MG
Initial University Lake Storage = 600 MG

Stone Quarry Working Volume (MG)	Initial SQ Storage Volume (MG)	Safe Yield (MGD)	
		Set 1A	Set 1B
0	0	21.19	20.15
50	50	21.40	20.24
100	100	21.61	20.33
150	150	21.82	20.43
200	200	22.03	20.52
250	200	22.24	20.61
300	200	22.43	20.70
350	200	22.50	20.80
400	200	22.53	20.89
450	200	22.56	20.98
500	200	22.59	21.07
600	200	22.64	21.26
700	200	22.70	21.45
800	200	22.76	21.63
900	200	22.82	21.79
1000	200	22.88	21.96
1200	200	23.00	22.29
1400	200	23.12	22.63
1600	200	23.24	22.96
1800	200	23.36	23.29
2000	200	23.48	23.56
2200	200	23.60	23.82
2400	200	23.72	24.08
2600	200	23.84	24.33
2800	200	23.95	24.59
3000	200	24.07	24.85

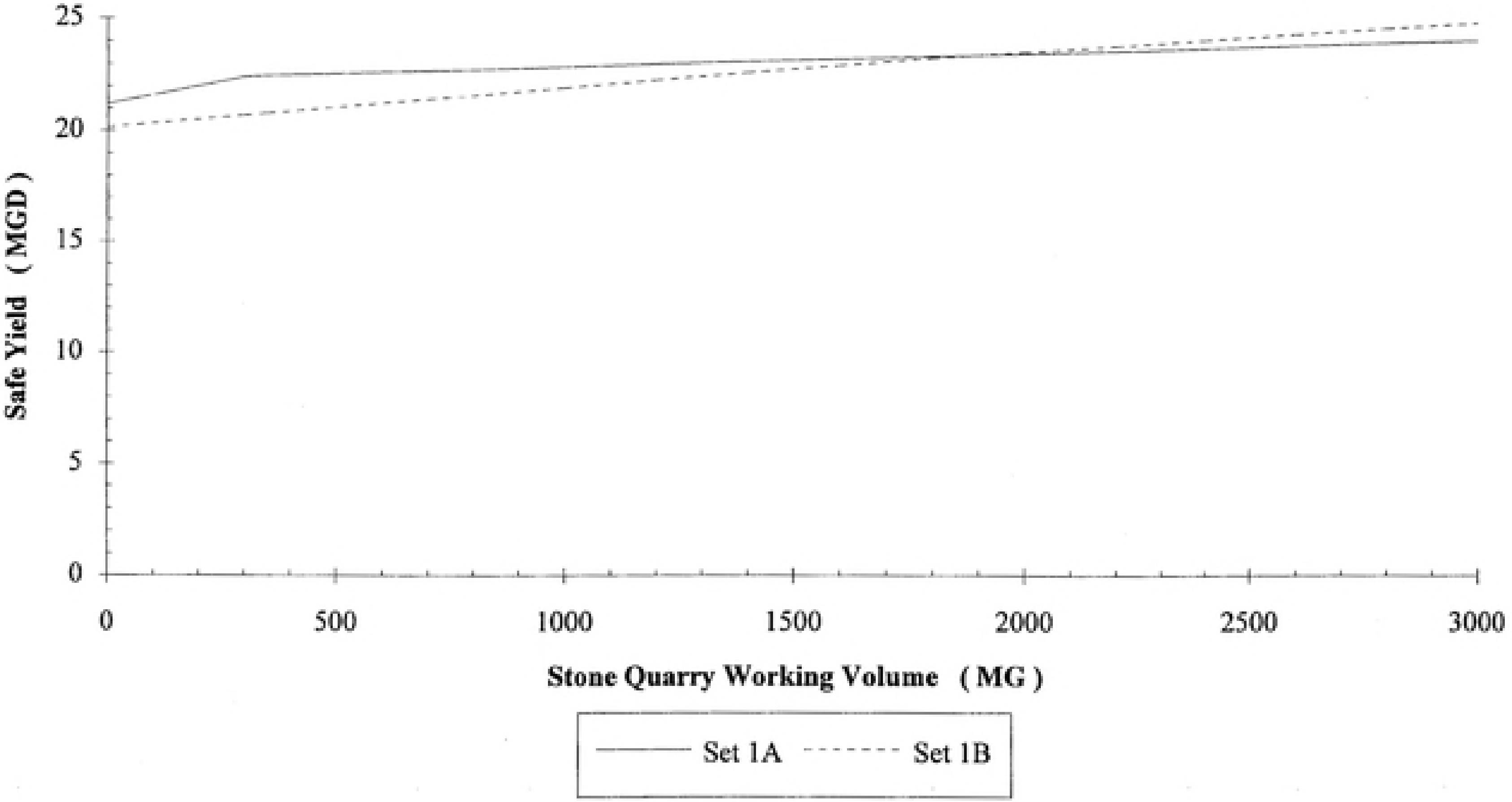
The safe yield values in Table 3.7 for Set 1A pertain to the historical inflow trace between October 1959 and September 1973. The values for Set 1B pertain to surrogate inflow values based on Flat River measurements. The comparison of the safe yield functions for these two inflow data sets is illustrated in Figure 3.3. The differences between Sets 1A and 1B yields are a measure of the "accuracy" of using the surrogate inflows.

Table 3.7 and Figure 3.3 indicate that the estimates of safe yields using the historical inflows and the surrogate inflows are in close agreement for all the trial SQ working volumes considered. That is, the "accuracy" of using the surrogate inflows for estimating the yield from the existing system is high. Furthermore, assuming that the characteristics of the watersheds did not change significantly over time, this implies that the surrogate inflows could be used to provide reasonable estimates of the system yield for periods in which no historical inflow data exists, making the Flat River-Cane Creek correlation an effective tool.

3.4.2 Sensitivity to Inflows

In this study, the sensitivity of the safe yield function for an expanding Stone Quarry to inflow conditions was investigated. The safe yield values obtained from the models utilizing Sets 1A, 2, 3, and 4 are reported in Table 3.8 for increasing SQ volumes, with UL and CC working volumes fixed at 600 MG and 3000 MG, respectively. The maximum capacities of University Lake and Cane Creek were used in this study because in the analyses of the isolated reservoirs, it was found that the influence of inflow conditions on the safe yield functions increased with increasing working volumes. Thus, the

Figure 3.3
Safe Yield for Existing OWASA System
Comparison of the Historical and Surrogate Inflow Results



Notes:
UL Working Volume = 600 MG
CC Working Volume = 3000 MG

Table 3.8
Existing System Safe Yield Study Results
Sensitivity to Inflows

Notes :

Set 1A - Historical Inflow Data from October 1959 to September 1973

Set 2 - Surrogate Inflow Data from October 1965 to September 1979

Set 3 - Surrogate Inflow Data from October 1970 to September 1984

Set 4 - Surrogate Inflow Data from October 1975 to September 1989

Cane Creek Storage Capacity fixed at 3000 MG

University Lake Storage Capacity fixed at 600 MG

Initial Conditions : Initial Cane Creek Storage = 3000 MG
Initial University Lake Storage = 600 MG

Stone Quarry Working Volume (MG)	Initial SQ Storage Volume (MG)	Safe Yield (MGD)			
		Set 1A	Set 2	Set 3	Set 4
0	0	21.19	18.95	18.95	18.95
50	50	21.40	19.04	19.04	19.04
100	100	21.61	19.12	19.12	19.12
150	150	21.82	19.20	19.20	19.20
200	200	22.03	19.29	19.29	19.29
250	200	22.24	19.37	19.37	19.37
300	200	22.43	19.45	19.45	19.45
350	200	22.50	19.54	19.54	19.54
400	200	22.53	19.62	19.62	19.62
450	200	22.56	19.70	19.70	19.70
500	200	22.59	19.79	19.79	19.79
600	200	22.64	19.95	19.95	19.95
700	200	22.70	20.12	20.12	20.12
800	200	22.76	20.29	20.29	20.29
900	200	22.82	20.45	20.45	20.45
1000	200	22.88	20.62	20.62	20.62
1200	200	23.00	20.95	20.95	20.95
1400	200	23.12	21.29	21.29	21.29
1600	200	23.24	21.62	21.62	21.62
1800	200	23.36	21.95	21.95	21.95
2000	200	23.48	22.29	22.29	22.13
2200	200	23.60	22.62	22.62	22.13
2400	200	23.72	22.65	22.95	22.13
2600	200	23.84	22.65	23.29	22.13
2800	200	23.95	22.65	23.62	22.13
3000	200	24.07	22.65	23.95	22.13

sensitivity of the safe yield function for an expanding SQ to the different inflow data sets would be less with smaller UL and CC working volumes.

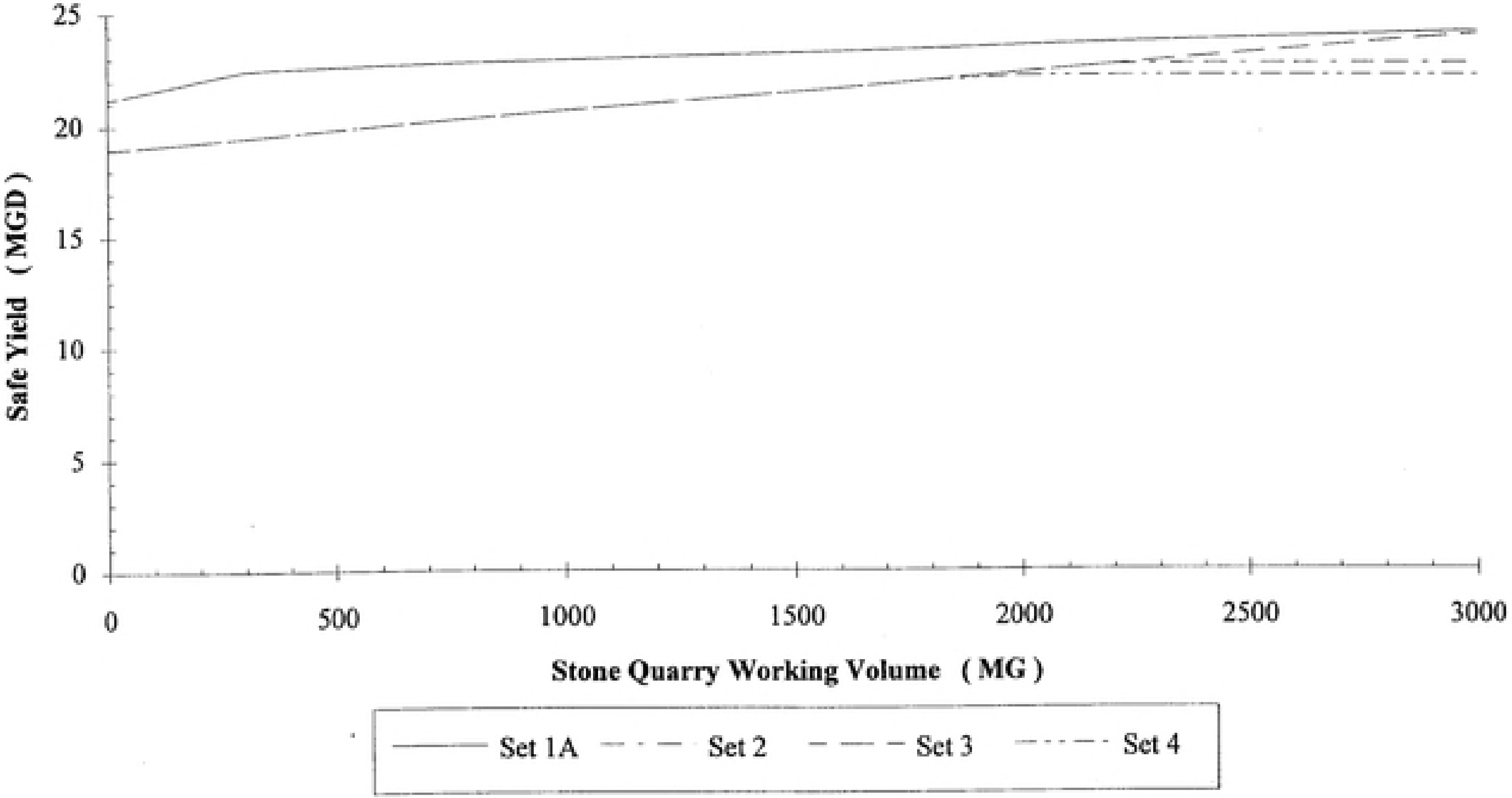
The safe yield functions, shown graphically in Figure 3.4, illustrate little sensitivity to inflow conditions. The results do not vary between Sets 2, 3, and 4 except for very large Stone Quarry working volumes. The safe yield values from Set 1A are generally higher than those of the other inflow sets. However, the differences in values are modest.

Figure 3.4 shows that the safe yield curves are rather flat. Considering the results from Sets 2, 3, and 4 for SQ working volumes between 0 and 1800 MG, the marginal increase in safe yield is nearly constant at 0.00167 MGD per MG. Expansion of SQ from 200 MG to 3000 MG would increase the safe yield of the system by as little as 2 MGD or as much as 4.7 MGD. This suggests that expansion of Stone Quarry capacity is of little benefit. However, this small marginal increase in yield assumes that the University Lake and Cane Creek reservoirs can fluctuate from full to empty. If UL and CC were constrained to reasonable working volumes (based on drawdown not to exceed, say, ten feet), the marginal yield obtained by increasing Stone Quarry capacity would be much greater.

3.4.3 Sensitivity to Working Volumes

The question of working volumes for University Lake and Cane Creek is central to this safe yield analysis. The potential payoff from expanding Stone Quarry capacity depends on the amounts by which OWASA is willing to allow water levels to fluctuate in its reservoirs. Similarly, the issue of when OWASA may want to augment its water supply via major capital improvements hinges on the question of working volumes. The

Figure 3.4
Safe Yield for Existing OWASA System
Sensitivity to Inflows



Notes:
UL Working Volume = 600 MG
CC Working Volume = 3000 MG

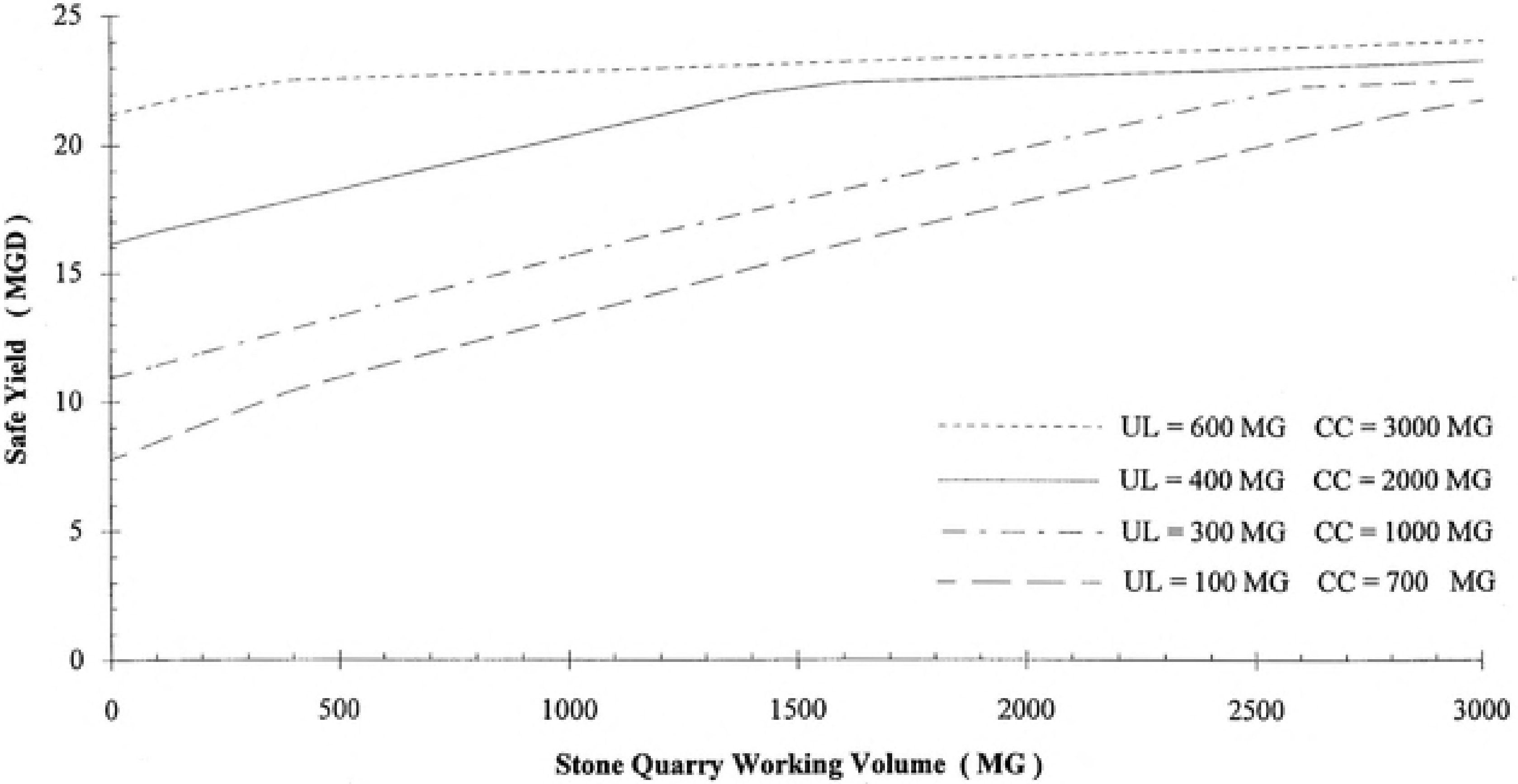
definition of the relationship between system yield and SQ expansion for various working volumes would be helpful in deciding working volumes for CC and UL in the future.

Appendix B contains the results from the sensitivity analyses made. The working volumes considered for UL were 100, 200, 300, 400, 500, and 600 MG. The working volumes of CC included in the study were 700, 1000, 1500, 2000, 2500, and 3000 MG. Only the historical inflow data of Set 1A was used because it was considered to be the most reliable and, as described in section 3.4.2, little sensitivity to inflows was found in the safe yields. The safe yield function with an expanding Stone Quarry was evaluated for all combinations of these working volumes. Figure 3.5 compares four of these safe yield functions.

As expected, the marginal contribution to the system safe yield was found to be greater for lower CC and UL working volumes as Stone Quarry initially expands. Figure 3.5 illustrates that at a given SQ volume, the slopes of the safe yield functions are steeper for lower UL and CC working volumes. This implies that the payoff from expanding SQ, in terms of marginal increases in safe yield, is higher if the working volumes of UL and CC are restricted. There are many other possible benefits that can result from further restraining the drawdown at UL and CC, such as improvements in water quality.

Another important result is that all the safe yield functions converge to approximately the same safe yield value as SQ expands to its maximum possible extent of 3000 MG. For example, the reliable yield of the existing OWASA reservoir configuration is estimated to be about 22 MGD for a Cane Creek working volume of 700 MG, a University Lake working volume of 100 MG, and Stone Quarry expanded to 3000 MG. This compares to the safe yield value of 24 MGD with the CC and UL working volumes equal to their maximum storage capacities of 3000 MG and 600 MG, respectively, and a

Figure 3.5
Safe Yield for Existing System
Sensitivity to Working Volumes



Notes:
Using Inflow Data Set 1A

Stone Quarry volume of 3000 MG. Therefore, with the unrestricted expansion of SQ to around 3000 MG, the working volumes of Cane Creek and University Lake could be decreased without significantly reducing the reliable yield from the entire system, while benefiting water quality and recreation uses.

3.4.4 Expansion of the Current OWASA System via Stone Quarry

Results presented in this subsection apply to the very important situation of the expansion of Stone Quarry with the working volumes of CC and UL fixed at 1300 MG and 450 MG, respectively. This portrays the expansion of the currently defined OWASA reservoir system. This University Lake working volume corresponds to the maximum possible drawdown to the lowest intake port, which is 12 feet. The working volume for CC represents an estimate of the volume available before the quality of water drawn from the lower depths of the reservoir is considered unacceptable. It is likely that OWASA will continue this operating policy of limiting the drawdown of the reservoirs to approximately 10 feet.

The results from the safe yield model using the historical inflow data for this situation are given in Table 3.9 and Figure 3.6. With the current SQ working volume of 200 MG, the model estimated a maximum constant yield from the OWASA system of about 14 MGD. This represents an estimate of the water supply capacity of the currently defined OWASA reservoir system. If Stone Quarry were expanded to 1000 MG, the system safe yield would increase to about 17.6 MGD. With the expansion of Stone Quarry to the maximum conceivable level of 3000 MG, the reliable yield of the system is predicted to increase to about 23 MGD.

Table 3.9
Safe Yield with Stone Quarry Expansion

Notes :

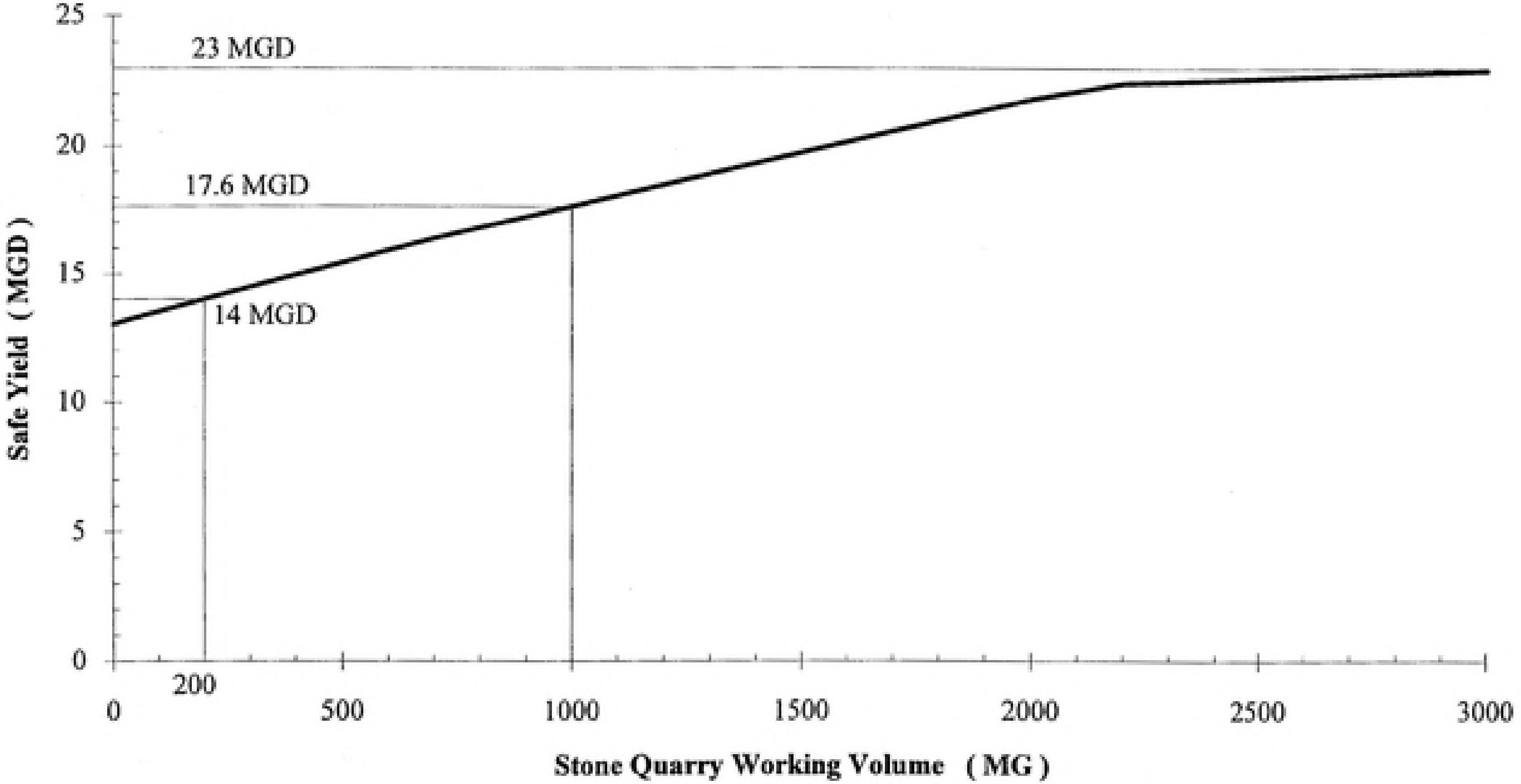
Using Inflow Data Set 1A - Historical Inflow Data

Cane Creek Working Volume fixed at 1300 MG

University Lake Working Volume fixed at 450 MG

Stone Quarry Working Volume (MG)	Initial SQ Storage Volume (MG)	Safe Yield (MGD)
0	0	13.06
50	50	13.29
100	100	13.53
150	150	13.77
200	200	14.01
250	200	14.25
300	200	14.48
350	200	14.72
400	200	14.96
450	200	15.20
500	200	15.44
600	200	15.91
700	200	16.39
800	200	16.82
900	200	17.24
1000	200	17.65
1200	200	18.49
1400	200	19.32
1600	200	20.15
1800	200	20.99
2000	200	21.82
2200	200	22.44
2400	200	22.56
2600	200	22.68
2800	200	22.81
3000	200	22.93

Figure 3.6
Safe Yield Versus Stone Quarry Expansion



Notes: Existing System
Using Inflow Data Set 1A
Cane Creek Working Volume = 1300 MG
University Lake Working Volume = 450 MG

The safe yield function shown in Figure 3.6 demonstrates diminishing returns to safe yield for increasing SQ working volume. Beyond a SQ working volume of about 2200 MG, the marginal increase in the reliable yield is predicted to be negligible. This implies that if the working volumes of Cane Creek and University Lake were maintained at about 1300 MG and 450 MG, respectively, expansions beyond 2200 MG would not result in appreciable further increases in safe yield.

As mentioned in section 3.3, if University Lake and Cane Creek were each operated independently at their normal working volumes, the total safe yield from the system (for the case of no Stone Quarry) would be about 12.8 MGD based on the historical inflow data. With the Stone Quarry working volume equal to zero, Table 3.9 gives the total yield from a jointly operated OWASA system as about 13 MGD. Thus, the joint operation of University Lake and Cane Creek provides a slightly higher total yield than if the reservoirs were operated independently. This is because interbasin transfers from the Cane Creek watershed to the University Lake reservoir are possible if the OWASA system is taken as a whole.

3.5 SAFE YIELD ANALYSIS OF THE MODIFIED OWASA SYSTEM

The final safe yield study considered a modified OWASA reservoir system in which pumping from University Lake to Stone Quarry was permitted. In essence, this modification allows Stone Quarry to serve as a storage basin for both the Cane Creek and University Lake watersheds. In the analyses of section 3.4, Stone Quarry augmented the storage only in the Cane Creek watershed. The re-piped Stone Quarry configuration was investigated to assess the potential for more fully developing the flows from both the University Lake and Cane Creek watersheds.

The safe yield model for this modified OWASA system was formulated as a linear program in section 2.4. Only the historical inflow data of Set 1A was incorporated in the LP model. From this model, estimates of the sustainable yield from the modified OWASA system for increasing Stone Quarry working volumes were obtained. Table 3.10 compares the safe yield values estimated for the existing system and the modified system for the case where the CC and UL working volumes were restricted to their present allowable values of 1300 MG and 450 MG, respectively. The results are presented graphically in Figure 3.7.

There is no difference between the safe yield functions for the existing configuration and the modified configuration within the range of conceivable expansions of Stone Quarry (i.e., SQ working volumes less than 3000 MG). In fact, the results indicate that Stone Quarry must be expanded beyond 18,000 MG before the safe yield from the modified system would be higher than that from the existing system, and even then, the difference is slight. This implies that there would be no advantage in re-piping Stone Quarry to serve both the UL and CC watersheds.

This is surprising in view of the small working volume of University Lake versus its relatively large drainage area. Graphs of reservoir storage over time are helpful in illustrating why the safe yields from the existing and modified systems are the same. The results presented in Figure 3.8 were obtained from the model for the existing system with a Stone Quarry working volume of 1000 MG, the normal working volumes for UL and CC, and the historical inflow data set. In Figure 3.8, the optimal storage volumes in each of the reservoirs are given for the 168 monthly time periods. Figure 3.9 is the corresponding graph for the modified system. In both Figure 3.8 and 3.9, there is only one critical interval when all three reservoirs are empty. This critical interval occurs around the 137th monthly time period. Just prior to the critical interval, the full working

Table 3.10
Comparison of the Existing System to the Modified System

Notes :

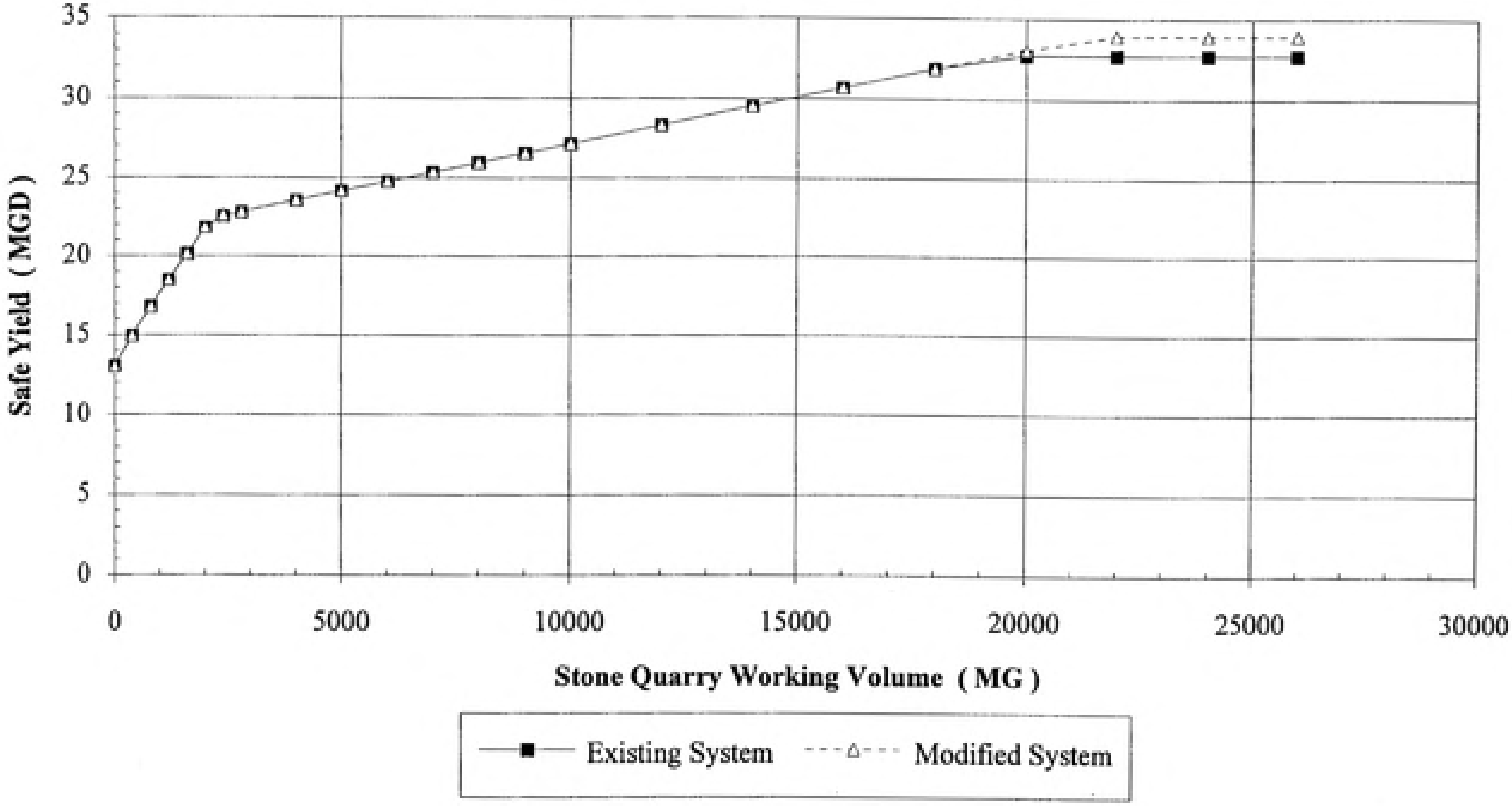
Using Inflow Data Set 1A - Historical Inflow Data

Cane Creek Working Volume fixed at 1300 MG

University Lake Working Volume fixed at 450 MG

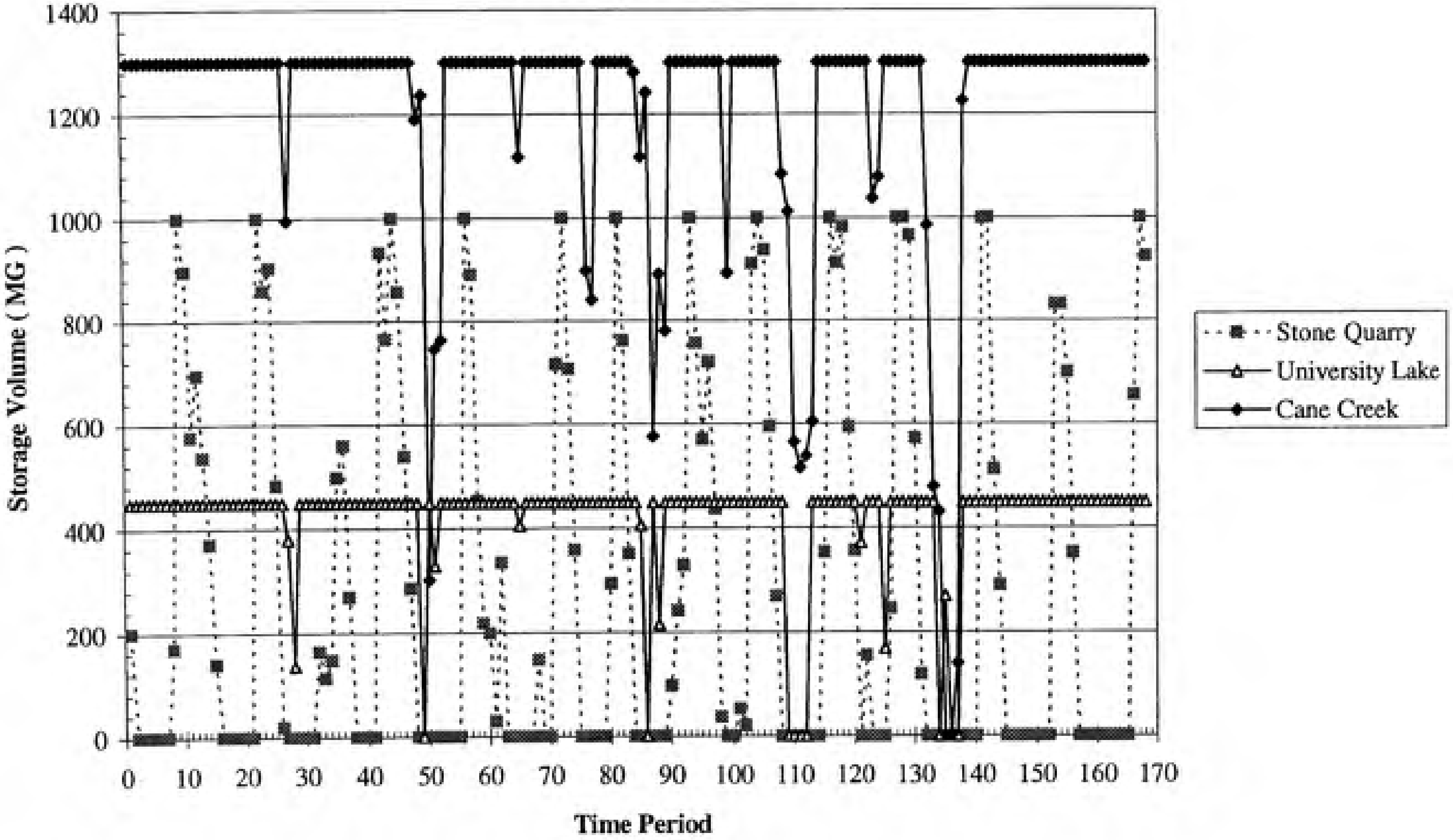
Stone Quarry Working Volume (MG)	Initial SQ Storage Volume (MG)	Safe Yield (MGD)	
		Existing	Modified
0	0	13.06	13.06
400	200	14.96	14.96
800	200	16.82	16.82
1200	200	18.49	18.49
1600	200	20.15	20.15
2000	200	21.82	21.82
2400	200	22.56	22.61
2800	200	22.81	22.85
3000	200	22.93	22.97
4000	200	23.55	23.57
5000	200	24.16	24.16
6000	200	24.76	24.76
7000	200	25.35	25.35
8000	200	25.95	25.95
9000	200	26.54	26.54
10000	200	27.14	27.14
12000	200	28.33	28.33
14000	200	29.52	29.52
16000	200	30.71	30.71
18000	200	31.90	31.90
20000	200	32.75	33.09
22000	200	32.75	33.99
24000	200	32.75	33.99

Figure 3.7
Comparison of the Existing System to the Modified System
with Stone Quarry Expansion



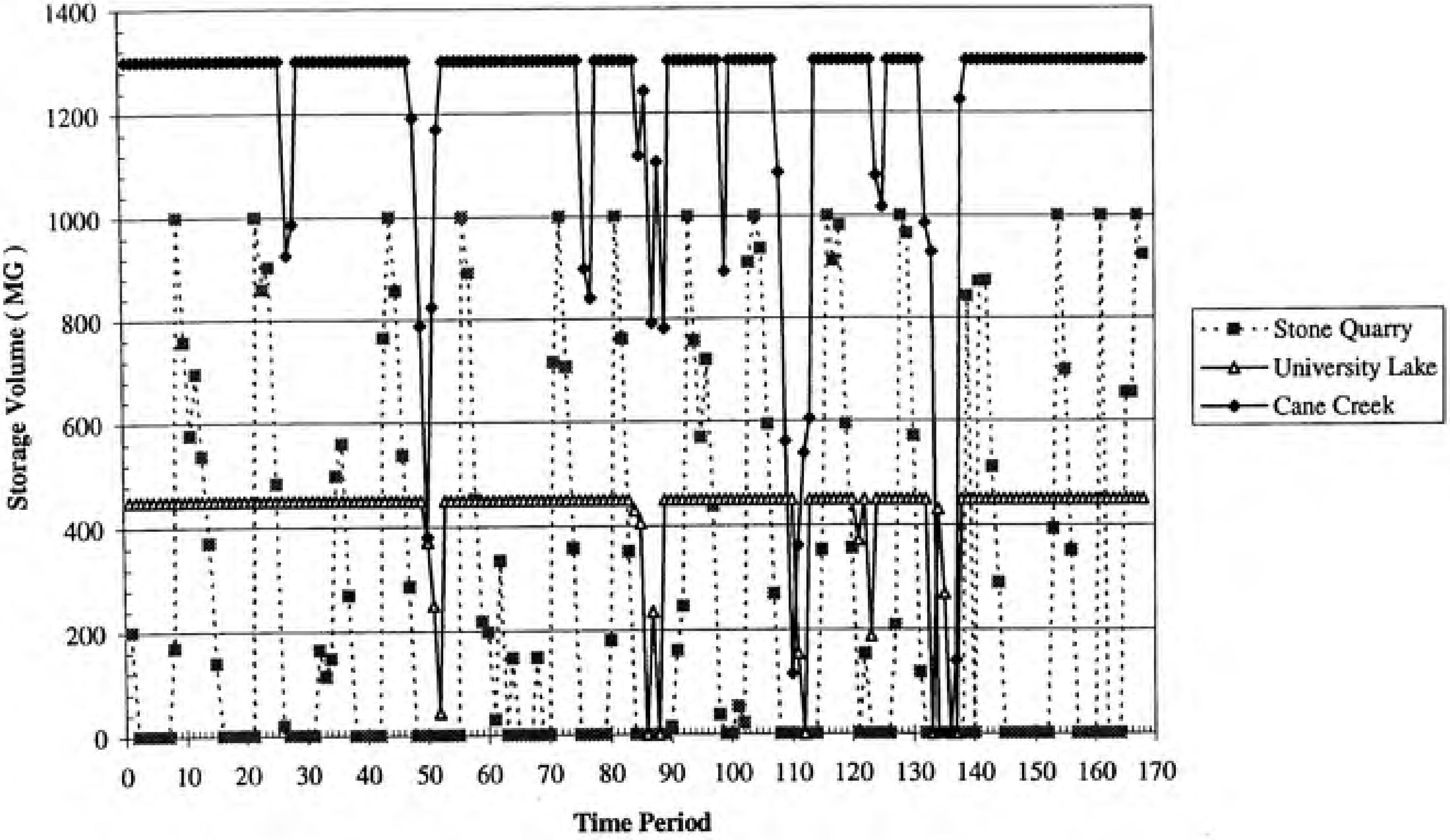
Notes :
Using Inflow Data Set 1A
Cane Creek Working Volume = 1300 MG
University Lake Working Volume = 450 MG

Figure 3.8
Graph of Storages versus Time for the Existing System
with SQ Working Volume = 1000 MG



Notes:
Using Inflow Data Set 1A
UL Working Volume = 450 MG
CC Working Volume = 1300 MG

Figure 3.9
Graph of Storages versus Time for the Modified System
with SQ Working Volume = 1000 MG



Notes:
Using Inflow Data Set 1A
UL Working Volume = 450 MG
CC Working Volume = 1300 MG

volumes are available at each reservoir for both the existing and modified systems. The safe yields from the existing and modified configurations are equal because the same volume of water is available to be distributed over the same critical interval.

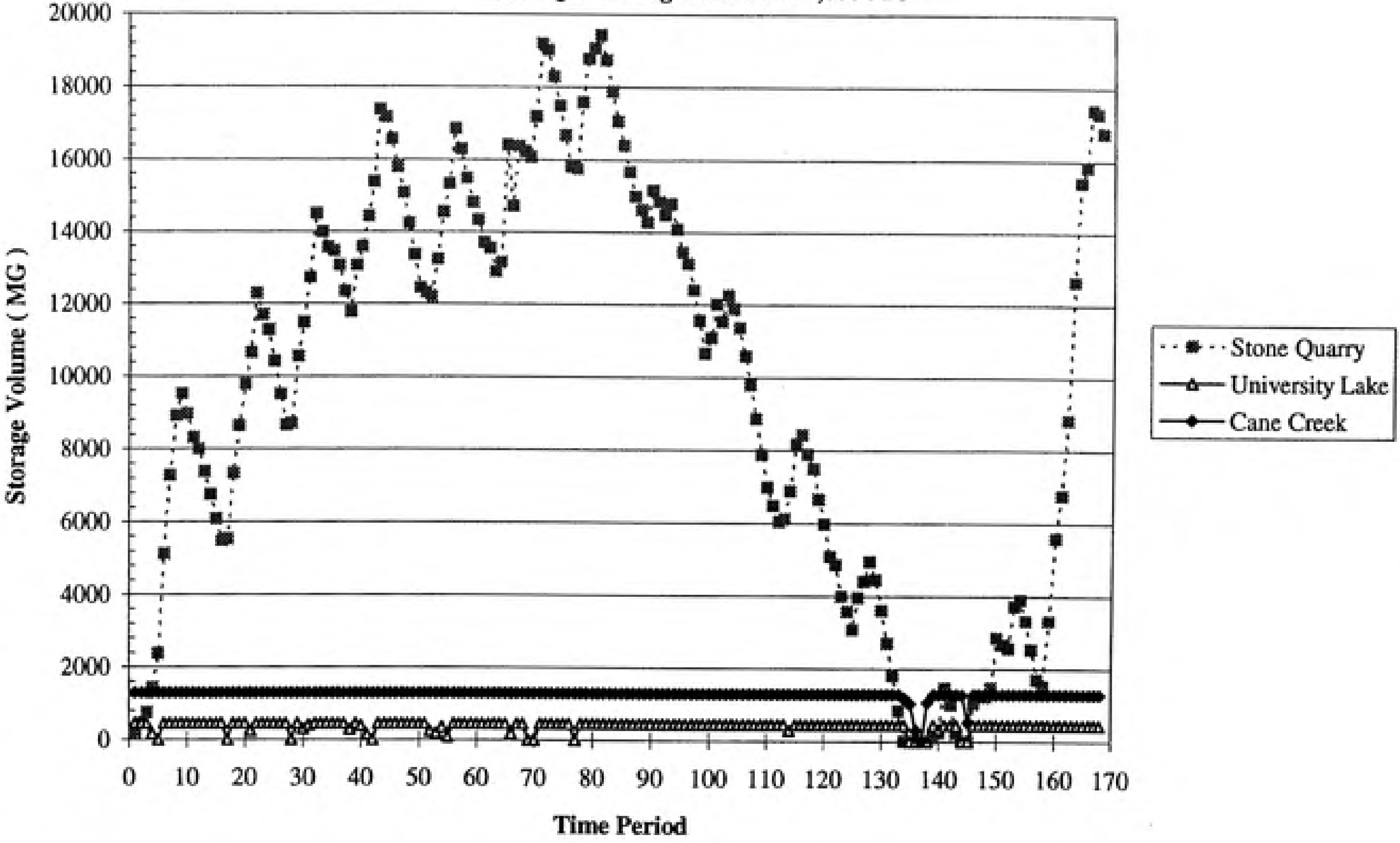
As long as the inflows are sufficient to fill the reservoirs just before the beginning of the critical interval, the safe yields will be equal. For SQ working volumes less than 20,000 MG, the flows from the Cane Creek watershed are able to fill the Stone Quarry reservoir, so that flows from the University Lake watershed are not required. Therefore, re-piping Stone Quarry does not provide additional storage. Figure 3.10 and Figure 3.11 are graphs of reservoir storages versus time for the existing and modified systems, respectively, with a Stone Quarry working volume of 24,000 MG. Under the existing configuration, the flows from the CC watershed are able to fill Stone Quarry to a maximum of about 19,000 MG before the critical interval. This uses all the inflows to Cane Creek. With the modified system, the re-piped Stone Quarry can be filled to a maximum of roughly 22,000 MG prior to the critical interval, which fully utilizes the flows from both the CC and UL watersheds. This additional 3,000 MG of SQ storage does not provide a significant increase in safe yield because it is distributed over a long time interval, i.e., the interval between when the SQ storage reaches its maximum value to when SQ completely empties.

3.6 SUMMARY

The following briefly summarizes the major findings of the safe yield analyses.

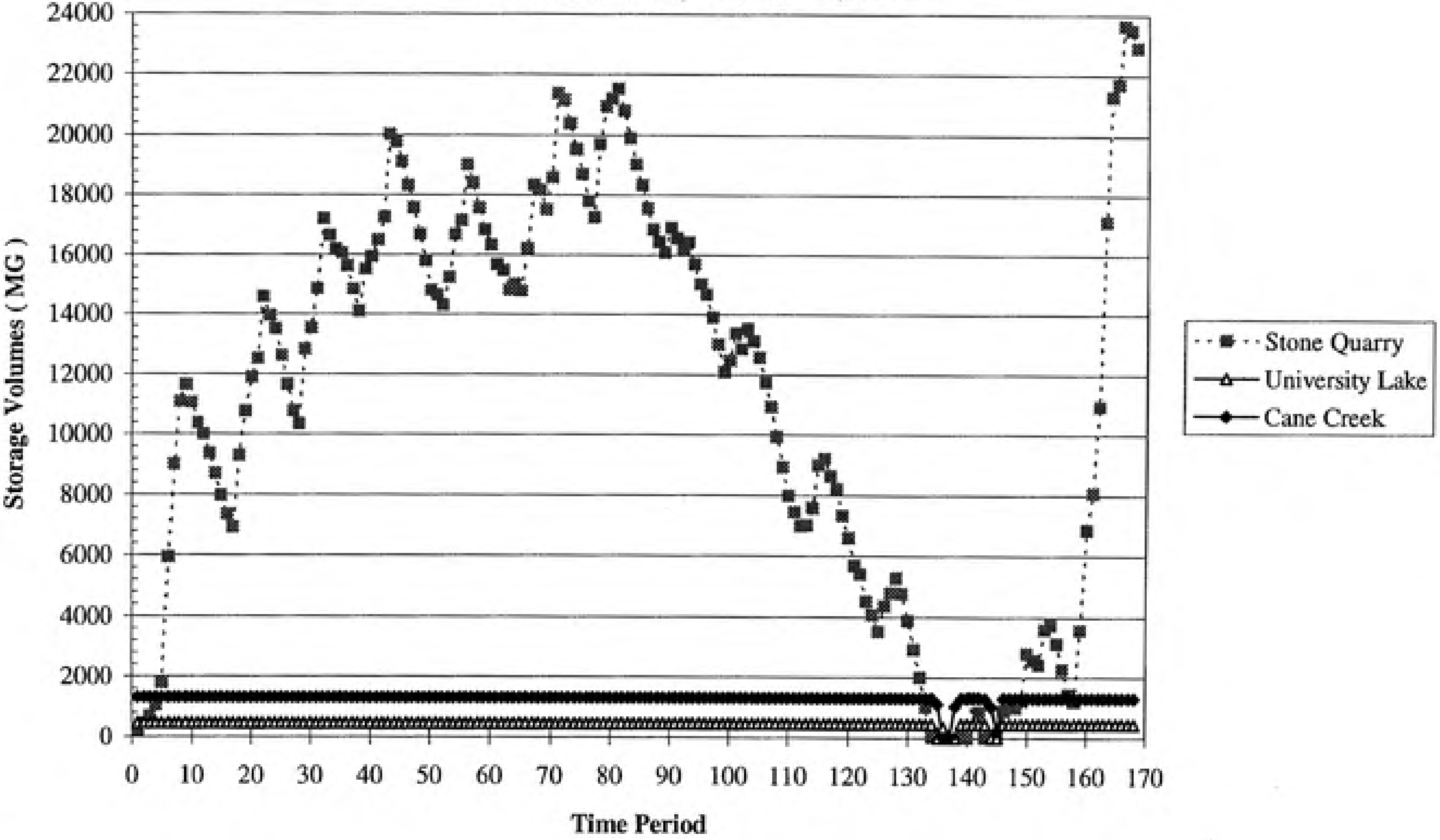
- The "Flat River at Bahama" gauging station was found to be a good surrogate for the discontinued "Cane Creek at Teer" station. A seasonal model describes the Flat River correlation with Cane Creek data.

Figure 3.10
Graph of Storages versus Time for the Existing System
with SQ Working Volume = 24,000 MG



Notes:
Using Inflow Data Set 1A
UL Working Volume = 450 MG
CC Working Volume = 1300 MG

Figure 3.11
Graph of Storages versus Time for the Modified System with SQ Working Volume = 24,000 MG



Notes:
Using Inflow Data Set 1A
UL Working Volume = 450 MG
CC Working Volume = 1300 MG

- With a working volume of 1300 MG, the safe yield of an isolated Cane Creek reservoir would be about 8.7 MGD.

- An isolated University Lake reservoir would produce a safe yield of approximately 4.1 MGD with a working volume of 450 MG.

- It is estimated that the currently defined OWASA reservoir system can provide a consistent total raw water supply of about 14 MGD.

- The safe yield function defining the reliable yield from the currently defined system with the expansion of Stone Quarry is given in Figure 3.6. Expanding Stone Quarry to 1000 MG would increase the system safe yield to about 17.6 MGD; expansion to 3000 MG would increase the yield to approximately 23 MGD.

- With the working volumes of University Lake and Cane Creek maintained at their present values of 450 MG and 1300 MG, expansion of Stone Quarry beyond 2200 MG would not provide significant returns to system safe yield. However, with the expansion of Stone Quarry to the maximum possible extent of 3000 MG, the working volumes of University Lake and Cane Creek could be reduced without substantially decreasing the system safe yield.

- Although the analyses of the isolated reservoirs indicated that there was potential for further developing the flow from both the Cane Creek and University Lake watersheds, the safe yield analysis of the modified system showed that re-piping Stone Quarry would not increase the safe yield of the system for the conceivable expansions of Stone Quarry.

4 COMPARISON OF EXPANSION ALTERNATIVES

In this section, the results from the safe yield models are applied to the long-range planning of the OWASA water supply system. OWASA's market is growing steadily and, in time, the excess capacity of the existing reservoir system will be exhausted. In planning for that condition, OWASA is currently considering two options for increasing its long-term water supply capacity: (1) expanding Stone Quarry, and (2) tapping a new water source, most likely Jordan Lake.

As described in section 1, the North Carolina Environmental Management Commission has granted OWASA a 10 MGD Level II water supply storage allocation from Jordan Lake. In 1989, OWASA purchased about 125 acres of land adjacent to Jordan Lake for potential use as a future pump station and water treatment plant site. OWASA has consulted with the firm CH2M HILL, who roughly estimated that the construction of a Jordan Lake intake structure and transmission system would cost about 19 million dollars (in August 1991 dollars). Transporting raw water from Jordan Lake to the existing WTP in Carrboro would require two-stage pumping.

The development of Jordan Lake as a water supply source will require a substantial and sustained financial commitment. Delay of the Jordan Lake option, especially via the inexpensive expansion of Stone Quarry, is likely to result in large present value savings. As a result, the optimal timing of the Jordan Lake project will be affected by the extent to which Stone Quarry reservoir is expanded.

OWASA's proposal for the quarry expansion is currently under debate. If the American Stone Company is allowed to extend its quarry operation onto OWASA-owned land, an eventual storage capacity of up to 3 billion gallons would be available once quarrying was complete around the year 2030. If the proposal is rejected, the expansion of Stone Quarry would be restricted to a maximum of about 1000 MG when quarrying reaches the end of the current property limits, which is likely to occur in 10 to 15 years.

The debate over the Stone Quarry expansion does not hinge only on OWASA's need for storage. The American Stone Company would like to extend its quarrying operation. The question that must be addressed is if the quarry expansion is allowed, what, if any, are the advantages to OWASA in terms of increased safe yield and present value savings. This requires a comparison of the various possible expansion scenarios.

4.1 OWASA DEMAND PROJECTIONS

To successfully plan for the expansion of a water resources system, accurate predictions of the demands to be met in the future are essential. OWASA estimates its present (1994) annual average daily demand as 7.5 MGD, which consists of the mostly residential demands of the Chapel Hill and Carrboro communities. In recent decades, this area has experienced substantial growth and development and the population of OWASA's service area is expected to continue to grow rapidly well into the next century.

A linear regression of OWASA's historical water sales indicated that the average daily demands (calculated on an annual basis) increased at a rate of about 0.178 MGD per year from 1976 to 1993 [OWASA, 1993]. This linear trend in the annual average water sales data had an R-squared of 0.96.

For long-range planning, OWASA water demands can also be assumed to be increasing at an average geometric growth rate of about 2.5 percent per annum [Black &

Veatch, 1992]. This value is based on the projected customer account growth rate and a usage per account analysis.

Both the linear and the geometric projections of OWASA water demands are considered in this analysis and values are given in Table 4.1 up to the year 2081. The two projections are shown graphically in Figure 4.1.

4.2 STONE QUARRY EXPANSION

Throughout this analysis, the working volumes of Cane Creek and University Lake were maintained at their present values of 1300 MG and 450 MG, respectively.

The potential rate of expansion of Stone Quarry is roughly estimated to be about 75 MG per year. This value assumes that Stone Quarry will expand from 200 MG in 1994 to 3000 MG in the year 2030 at a constant rate. Table 4.2 shows the potential SQ volumes available to OWASA over the next 36 years, assuming the unrestricted expansion of Stone Quarry. From the safe yield results presented in Figure 3.6, these potential Stone Quarry working volumes are converted to reliable yields. Thus, Table 4.2 gives the potential reliable yield obtainable from the OWASA system over time.

In Figure 4.2, the potential yield over time is given for the cases of the unrestricted and restricted expansions of Stone Quarry. With the current SQ working volume of 200 MG, the safe yield that can be obtained in the year 1994 is 14 MGD. A potential SQ working volume of 1000 MG is estimated to be available by around the year 2005. If the expansion of SQ is restricted to a maximum of 1000 MG, the potential yield over time would remain constant at 17.6 MGD for all years after 2005. However, with the unrestricted expansion of Stone Quarry to 3000 MG by the year 2030, the potential

Table 4.1
OWASA's Projected Annual Average Daily Water Demands

Year	Demands (MGD)		Year	Demands (MGD)	
	Linear	Geometric		Linear	Geometric
1994	7.50	7.50	2038	15.33	22.23
1995	7.68	7.69	2039	15.51	22.78
1996	7.86	7.88	2040	15.69	23.35
1997	8.03	8.08	2041	15.87	23.94
1998	8.21	8.28	2042	16.04	24.54
1999	8.39	8.49	2043	16.22	25.15
2000	8.57	8.70	2044	16.40	25.78
2001	8.75	8.92	2045	16.58	26.42
2002	8.92	9.14	2046	16.76	27.08
2003	9.10	9.37	2047	16.93	27.76
2004	9.28	9.60	2048	17.11	28.45
2005	9.46	9.84	2049	17.29	29.17
2006	9.64	10.09	2050	17.47	29.89
2007	9.81	10.34	2051	17.65	30.64
2008	9.99	10.60	2052	17.82	31.41
2009	10.17	10.86	2053	18.00	32.19
2010	10.35	11.13	2054	18.18	33.00
2011	10.53	11.41	2055	18.36	33.82
2012	10.70	11.70	2056	18.54	34.67
2013	10.88	11.99	2057	18.71	35.54
2014	11.06	12.29	2058	18.89	36.42
2015	11.24	12.60	2059	19.07	37.33
2016	11.42	12.91	2060	19.25	38.27
2017	11.59	13.23	2061	19.43	39.22
2018	11.77	13.57	2062	19.60	40.21
2019	11.95	13.90	2063	19.78	41.21
2020	12.13	14.25	2064	19.96	42.24
2021	12.31	14.61	2065	20.14	43.30
2022	12.48	14.97	2066	20.32	44.38
2023	12.66	15.35	2067	20.49	45.49
2024	12.84	15.73	2068	20.67	46.63
2025	13.02	16.13	2069	20.85	47.79
2026	13.20	16.53	2070	21.03	48.99
2027	13.37	16.94	2071	21.21	50.21
2028	13.55	17.36	2072	21.38	51.47
2029	13.73	17.80	2073	21.56	52.75
2030	13.91	18.24	2074	21.74	54.07
2031	14.09	18.70	2075	21.92	55.42
2032	14.26	19.17	2076	22.10	56.81
2033	14.44	19.65	2077	22.27	58.23
2034	14.62	20.14	2078	22.45	59.69
2035	14.80	20.64	2079	22.63	61.18
2036	14.98	21.16	2080	22.81	62.71
2037	15.15	21.69	2081	22.99	64.27

Figure 4.1
OWASA's Projected Average Daily Water Demands

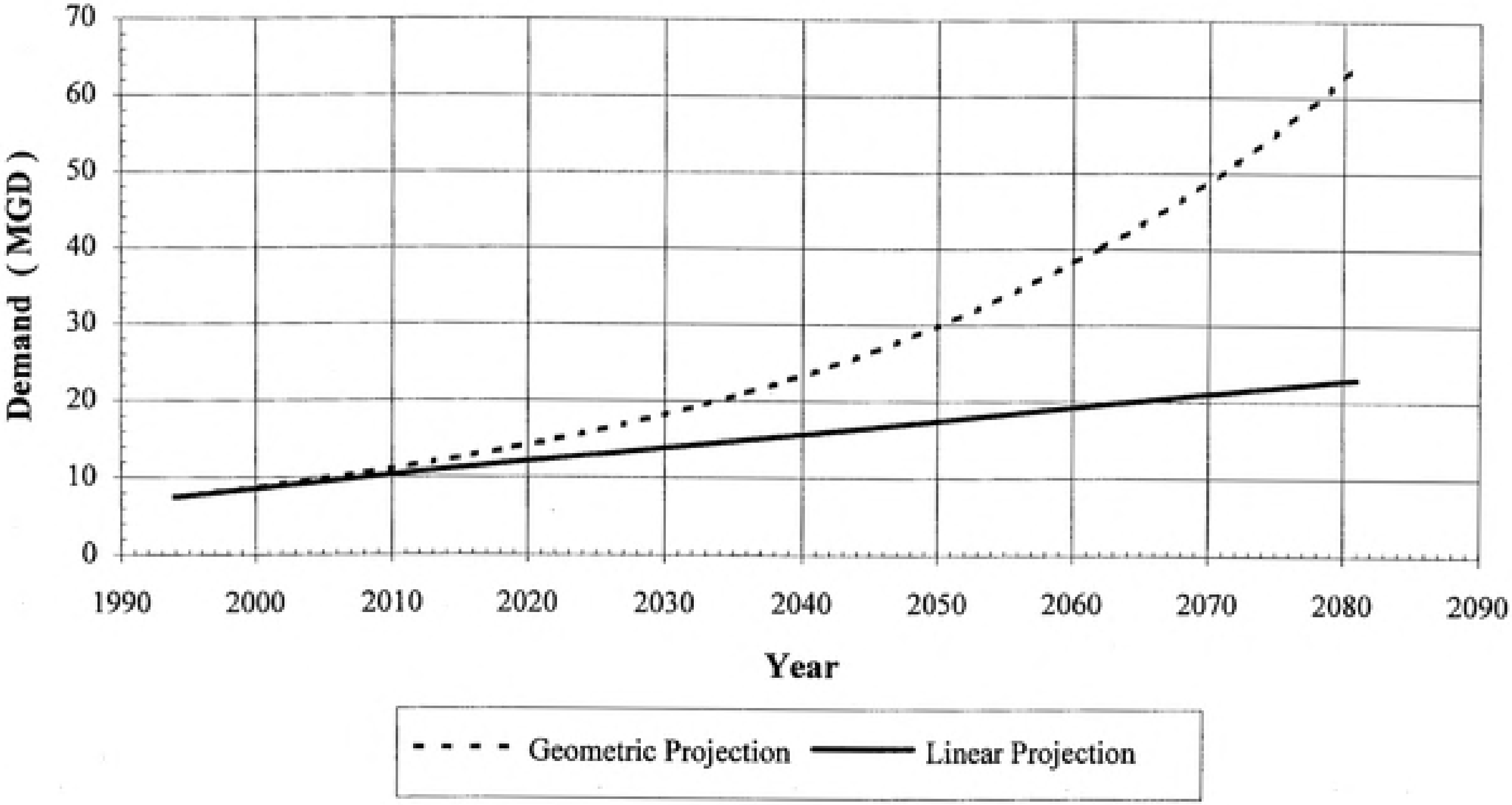
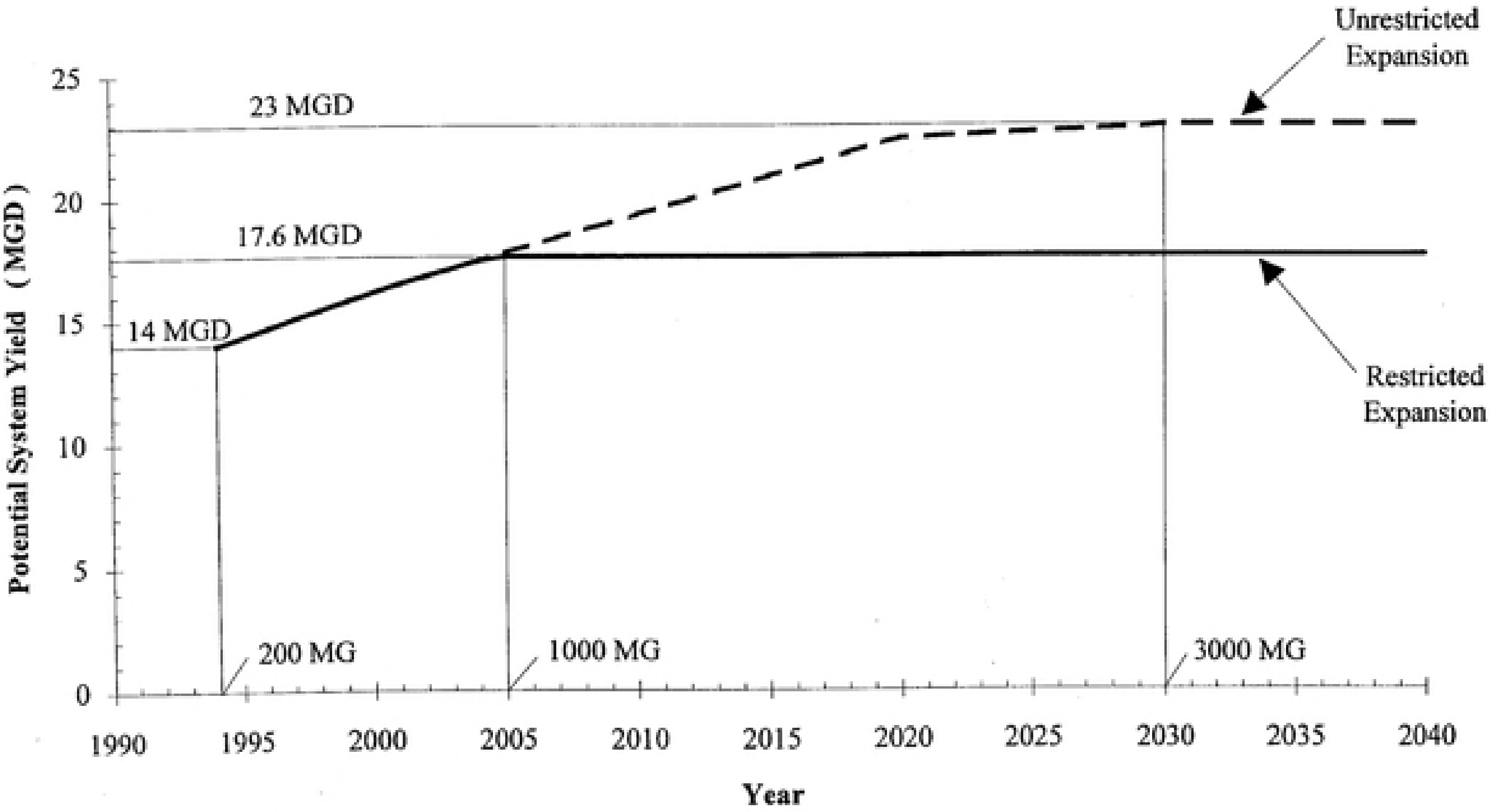


Table 4.2
Potential SQ Working Volumes and System Safe Yields Over Time

Year	Potential SQ Working Volume (MG)	Potential Safe Yield (MGD)
1994	200	14.01
1995	275	14.37
1996	350	14.72
1997	425	15.08
1998	500	15.44
1999	575	15.79
2000	650	16.15
2001	725	16.51
2002	800	16.82
2003	875	17.13
2004	950	17.44
2005	1025	17.76
2006	1100	18.07
2007	1175	18.38
2008	1250	18.69
2009	1325	19.01
2010	1400	19.32
2011	1475	19.63
2012	1550	19.94
2013	1625	20.26
2014	1700	20.57
2015	1775	20.88
2016	1850	21.19
2017	1925	21.51
2018	2000	21.82
2019	2075	22.13
2020	2150	22.41
2021	2225	22.45
2022	2300	22.50
2023	2375	22.54
2024	2450	22.59
2025	2525	22.64
2026	2600	22.68
2027	2675	22.73
2028	2750	22.78
2029	2825	22.82
2030	3000	22.93

Figure 4.2
Potential Yield Over Time



yield would continue to increase up to the year 2030. After the year 2030, the yield that potentially could be obtained from the OWASA reservoir system would remain constant at about 23 MGD.

The safe yield analysis shows that the reliable yield of the present OWASA system (i.e., with working volumes of 200 MG for Stone Quarry, 1300 MG for CC, and 450 MG for UL) is about 14 MGD. According to the linear demand projections, the present OWASA system can meet demands until about the year 2031. On the other hand, with the geometric demand projections, the excess capacity of the present OWASA system would be exhausted by about the year 2020. In general, the current OWASA reservoir system should be able to meet the average daily demand for the next 25 to 35 years.

Considering the linear demand projections, OWASA would have to augment its water supply capacity by the year 2031. There are three possible expansion scenarios. First, if Stone Quarry is not expanded at all, the Jordan Lake system would have to be ready to go on line by 2031. Second, if further expansion of the quarry operation is not permitted, the present boundary restrictions would limit the SQ expansion to about 1000 MG. With the restricted expansion of Stone Quarry, it can estimated from Figure 4.2 that the potential yield from the system in the year 2031 would be 17.6 MGD. In other words, the expansion of SQ to 1000 MG by the year 2031 would increase the reliable yield to about 17.6 MGD. This would allow OWASA to meet linearly increasing demands until around the year 2051. With no further expansion of Stone Quarry possible, OWASA would have to construct the Jordan Lake system by the year 2051. This expansion scenario is represented graphically in Figure 4.3.

In the third scenario, the quarry operation is allowed to expand. Figure 4.4 shows the staged development of Stone Quarry and the increase in the water supply capacity for

Figure 4.3
Capacity Expansion Planning with Restricted SQ Expansion and Linear Demand Projections

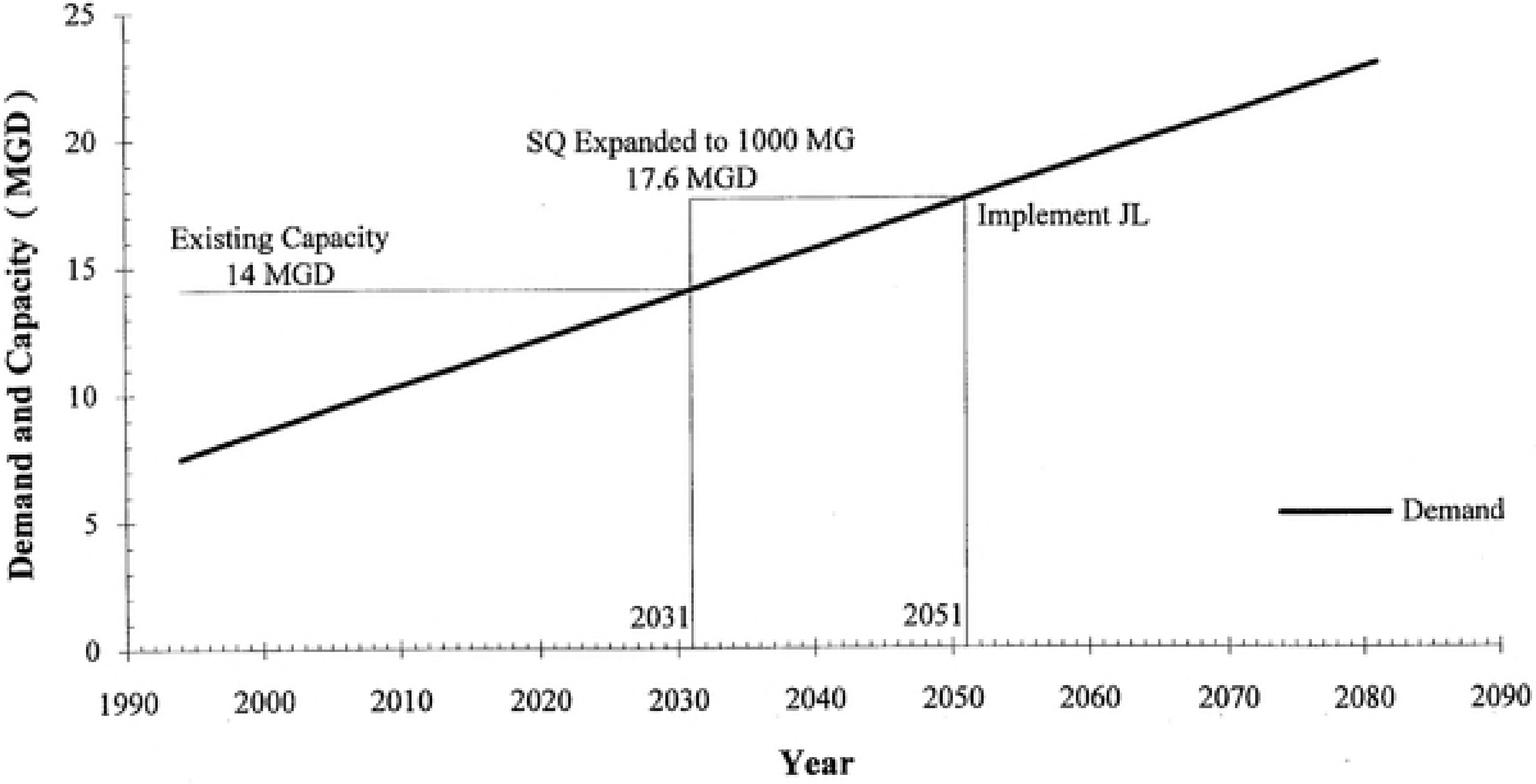
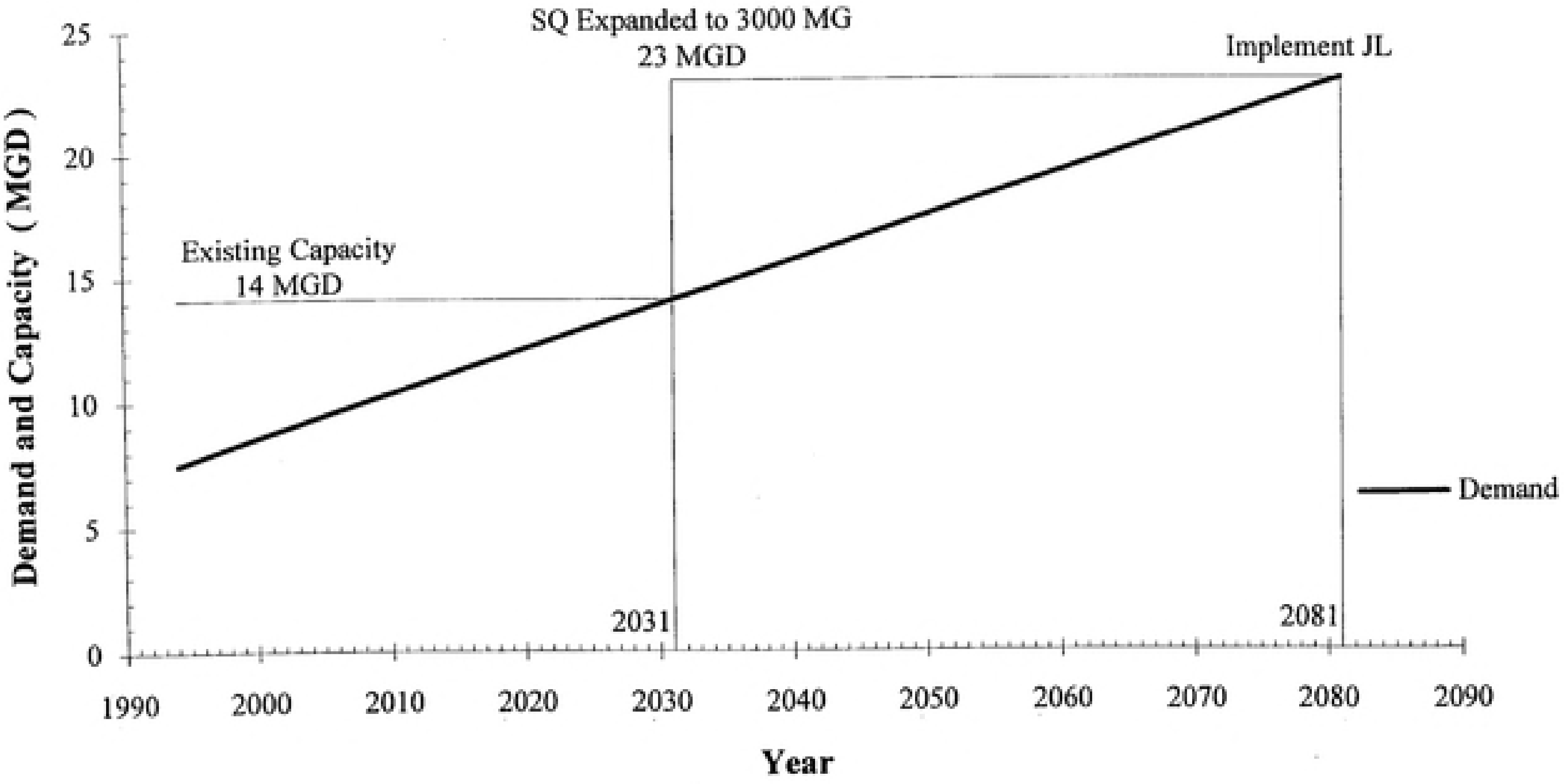


Figure 4.4
Capacity Expansion Planning with Unrestricted SQ Expansion and Linear Demand Projections



this scenario. From Figure 4.2, it can be noted that by the year 2031, the potential yield could be increased to about 23 MGD with the expansion of SQ to 3000 MG. This would meet the linear demand projections up to the year 2081 and the development of the Jordan Lake source would be required by that year because further expansion of SQ would be impossible.

The same type of analysis can be conducted assuming that demands are increasing geometrically. In this case, it would be necessary either to expand Stone Quarry by the year 2020, or have the Jordan Lake system ready to go on line by that time. Figure 4.5 gives the capacity expansion scheme corresponding to the restricted expansion of Stone Quarry (i.e., rejection of the quarry expansion proposal), while Figure 4.6 corresponds to the unrestricted expansion (i.e., approval of the proposal).

Figure 4.5 illustrates that the limited expansion of Stone Quarry to 1000 MG would enable OWASA to meet the geometric demand projections up to about the year 2029 by increasing the capacity of the system to approximately 17.6 MGD. Jordan Lake would be required to meet the predicted demands beyond 2029.

If the quarry operation is permitted to expand, it is estimated that a potential volume of about 2150 MG would be available at Stone Quarry by the year 2020 with a corresponding safe yield of 22.4 MGD. As Figure 4.6 indicates, the expansion of the capacity to 22.4 MGD would enable the system to meet demands until about the year 2039. By 2039, quarrying would be complete and there is the possibility that Stone Quarry could be expanded again to the maximum total volume of 3000 MG. However, the expansion from 2150 MG to 3000 MG would not increase the safe yield significantly. In fact, the potential yield of 23 MGD with a SQ working volume of 3000 MG would not meet the estimated demands for the year 2040. So, the expansion of Stone Quarry from

Figure 4.5
Capacity Expansion Planning with Restricted SQ Expansion
and Geometric Demand Projections

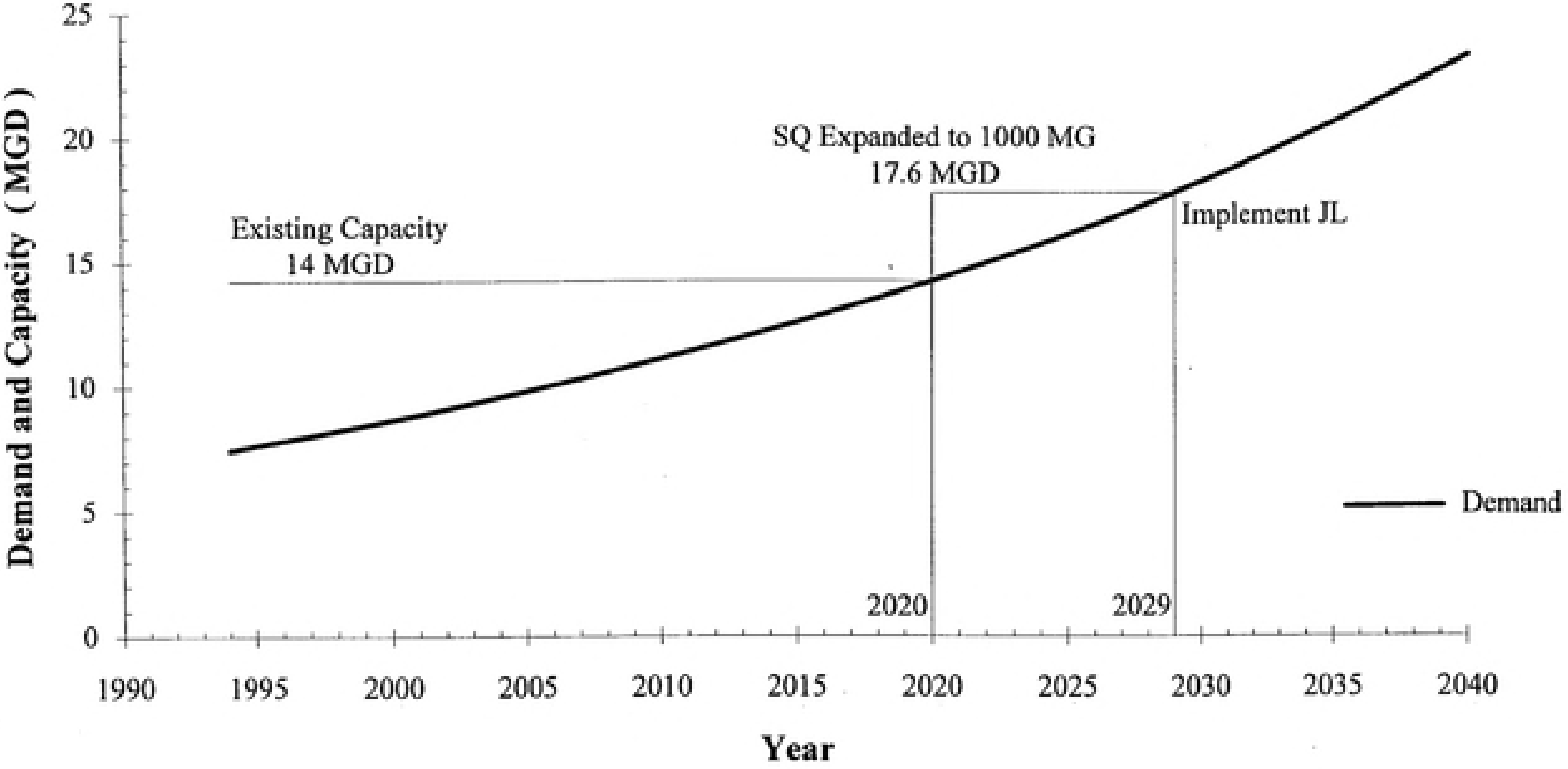
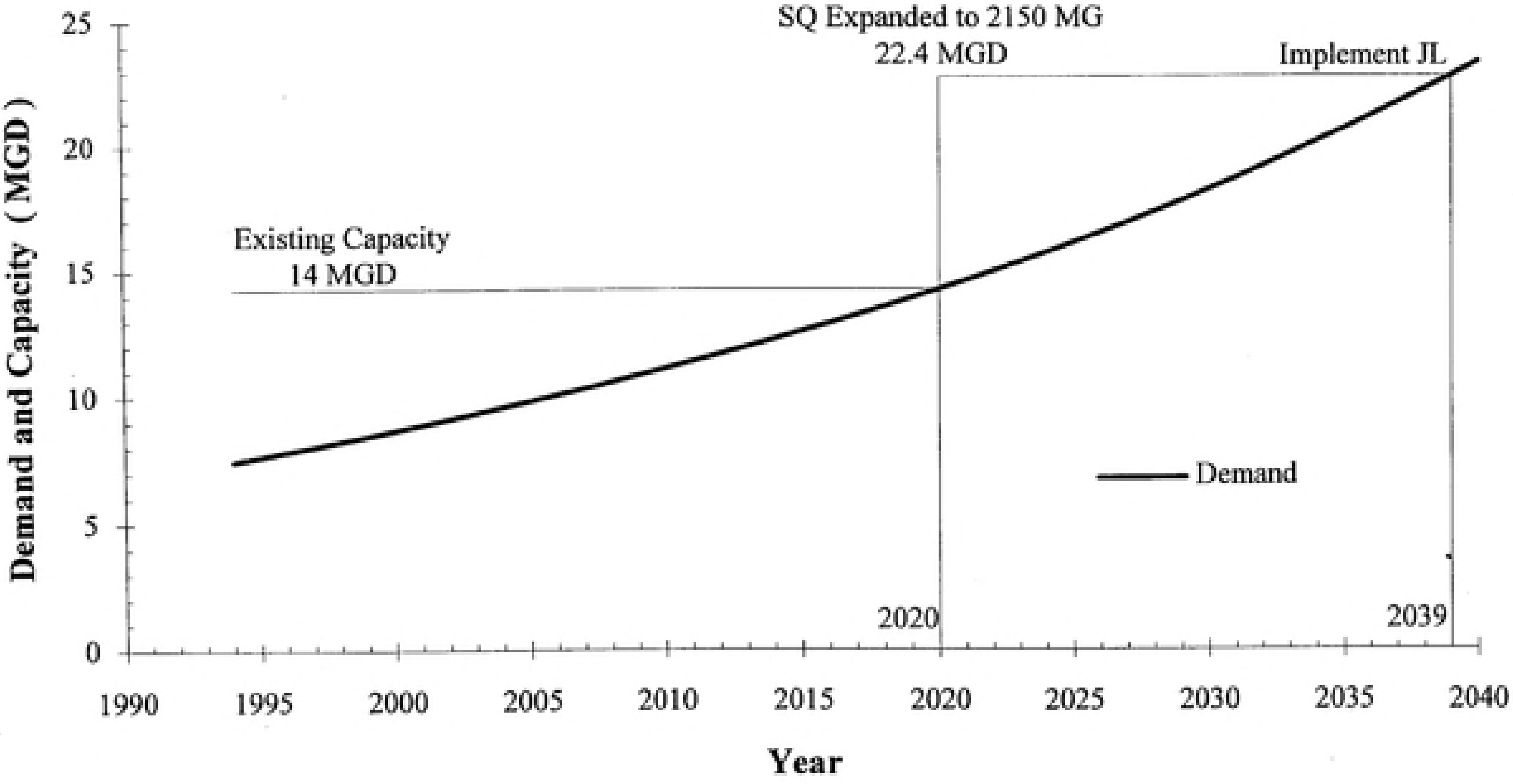


Figure 4.6
Capacity Expansion Planning with Unrestricted SQ Expansion and Geometric Demand Projections



2150 MG to 3000 MG would not significantly extend the excess capacity of the system, and the Jordan Lake option would have to be implemented by the year 2039.

4.3 PRESENT VALUE COST COMPARISON

The pecuniary costs associated with the expansion of Stone Quarry includes 20 years of land payments to the American Stone Company for the purchase of buffering land around the quarry site [OWASA, 1993]. OWASA is currently budgeting $35,000 per year for this project. Another cost of expanding Stone Quarry is the continuing need to spend $20,000 per year to maintain the option of tapping Jordan Lake in the future. However, expanding SQ has a major nonpecuniary cost, which is the cost associated with the public resistance over the quarry expansion proposal. This nonpecuniary cost was not considered in this present value cost analysis.

The total capital costs associated with tapping Jordan Lake was assumed to be $19 million in 1991 dollars [CH2M HILL, 1991]. CH2M HILL estimated that it would take approximately 6 years to construct the Jordan Lake system. However, the information available was insufficient to estimate the distribution of the capital costs over the implementation period. So, the entire capital cost was assumed to be incurred in the year in which the system starts operation.

In this analysis, the minimum attractive rate of return on OWASA's investments was taken as 10 % per year and an inflation factor of 2 % per year was assumed. Details of the present value cost calculations are presented in Appendix C. The results assuming a linear demand projection are given in Table 4.3 and those assuming a geometric demand projection are contained in Table 4.4.

Table 4.3
Present Value Costs
with Linear Demand Projections

Scenario	Description	Inflated Capital Costs Of JL Construction	Total P.V. Cost in 2031
1	**No SQ expansion** Implement JL by year 2031	$42.0 million (in 2031 dollars)	$ 42.0 million
2	**Restricted Expansion of SQ** Expand SQ to 1000 MG by 2031 Implement JL by 2051 Delays JL option by 20 years	$62.3 million (in 2051 dollars)	$19.6 million
3	**Unrestricted Expansion of SQ** Expand SQ to 3000 MG by 2031 Implement JL by 2081 Delays JL by 50 years	$112.9 million (in 2081 dollars)	$10.4 million

Table 4.4
Present Value Costs
with Geometric Demand Projections

Scenario	Description	Inflated Capital Costs Of JL Construction	Total P.V. Cost in 2020
1	**No SQ expansion** Implement JL by year 2020	$33.7 million (in 2020 dollars)	$ 33.7 million
2	**Restricted Expansion of SQ** Expand SQ to 1000 MG by 2020 Implement JL by 2029 Delays JL option by 9 years	$40.3 million (in 2029 dollars)	$20.8 million
3	**Unrestricted Expansion of SQ** Expand SQ to 2150 MG by 2020 Implement JL by 2039 Delays JL by 19 years	$49.2 million (in 2039 dollars)	$11.8 million

The total present value costs in Table 4.3 were calculated to the year 2031. This allows the costs of the different expansion scenarios to be compared in the year when the existing excess capacity of the system is predicted to be exhausted. If the quarry expansion proposal is rejected and Stone Quarry is expanded only to 1000 MG (Scenario 2), it is estimated that a present value saving of nearly $22 million would be achieved in the year 2031 compared to building the Jordan Lake system by 2031 (Scenario 1). That is, the delay of the Jordan Lake option by 20 years via the expansion of Stone Quarry would save about $22 million in 2031. If the quarry expansion plan is approved and unrestricted expansion of Stone Quarry is allowed (Scenario 3), the development of the Jordan Lake system could be delayed by 50 years, resulting in a present value saving in 2031 of approximately $32 million.

In the present value cost calculations using the geometric demand projections, the datum was taken at year 2020. If Stone Quarry were expanded to 1000 MG by 2020, which would delay the tapping of Jordan Lake by 9 years, a present value saving in 2020 of about $13 million would be achieved. With the approval of the quarry expansion proposal, the development of the Jordan Lake source could be delayed by 19 years. This would provide OWASA with a present value saving in 2020 of approximately $22 million.

This illustrates that the use of an expanded Stone Quarry when the present capacity of the system is exhausted would result in substantial present value savings compared to constructing the Jordan Lake system by that time. With demands increasing linearly, allowing the quarry operation to extend onto the OWASA-owned land would yield an additional present value saving in 2031 of about $9 million compared to limiting the quarry to its present boundaries. Similarly, with demands increasing at a growth rate of 2.5% per year, approval of the quarry expansion plan would result in an additional present value saving of about $9 million in the year 2020.

The above discussion assumes that OWASA's water demands will increase over the planning horizon without an upper bound. The possibility of an upper bound on OWASA's water demands is very material to the long-range planning of the water supply system. For example, it has been suggested that at saturation, OWASA's service area will have a maximum population of approximately 110,000 people. Assuming an average per capita usage of 140 gallons per capita per day, a rough estimate of the upper bound is 15.4 MGD. With the working volumes of University Lake and Cane Creek constrained to the normal values of 450 MG and 1300 MG, respectively, an expansion of Stone Quarry to 1000 MG, supplying a total system safe yield of 17.6 MGD, would suffice to meet this maximum average daily water demand. If this is the case, extension of the quarry operation onto OWASA-owned land and the development of the Jordan Lake source would not be needed. However, further research is required to properly investigate the influence of potential upper bounds on the long-range planning of the OWASA water supply system.

4.4 SUMMARY AND RECOMMENDATIONS

With demands predicted to be increasing linearly at 0.178 MGD per year :

- the present system capacity of 14 MGD would be exhausted by about the year 2031;
- if the quarry expansion proposal is rejected, expanding Stone Quarry to 1000 MG by the year 2031 would:
    - increase capacity to 17.6 MGD,
    - meet demands until the year 2051,
    - delay the Jordan Lake construction by about 20 years, and,
    - provide a present value saving in 2031 of about $22 million,

- if the quarry expansion proposal is approved, expanding Stone Quarry to 3000 MG by the year 2031 would:
    - increase capacity to 23 MGD,
    - meet demands until the year 2081,
    - delay the Jordan Lake construction by about 50 years, and,
    - provide a present value saving in 2031 of about $32 million.

With future demands predicted to be increasing at a growth rate of 2.5 % per year:

- the present system capacity of 14 MGD would be exhausted by about the year 2020;
- if the quarry expansion proposal is rejected, expanding Stone Quarry to 1000 MG by the year 2020 would:
    - increase capacity to 17.6 MGD,
    - meet demands until the year 2029,
    - delay the Jordan Lake construction by about 9 years, and,
    - provide a present value saving in 2020 of about $13 million;
- if the quarry expansion proposal is approved, expanding Stone Quarry to 2150 MG by the year 2020 would:
    - increase capacity to 22.4 MGD,
    - meet demands until the year 2039,
    - delay the Jordan Lake construction by about 19 years, and,
    - provide a present value saving in 2020 of about $22 million.

In general, it is recommended that :

- by the time the present capacity is exhausted, Stone Quarry should at least be expanded to the maximum possible extent within the current boundaries of the quarry site,

- OWASA should compare the nonpecuniary cost of public resistance to the additional savings obtained with the approval of the quarry expansion proposal to decide whether the debate is worthwhile (e.g., is the public controversy worth saving $9 million in the year 2020),

- OWASA should consider whether it is worthwhile to expand Stone Quarry beyond about 2200 MG because such expansions would provide negligible increases to the system safe yield with the present working volumes of University Lake and Cane Creek, but may enable the working volumes of University Lake and Cane Creek to be reduced without significantly changing the safe yield,

- if Stone Quarry becomes a major component of the water supply system, OWASA should investigate the improvement of the pumping facilities at Stone Quarry, possibly including the installation of a main from Stone Quarry directly to the WTP because such improvements would reduce the operating (i.e., pumping) costs of using the Stone Quarry reservoir, and,

- OWASA should take steps (if necessary) to ensure the continued operation of the "Flat River at Bahama" gauging station because the site, in conjunction with the correlation between the Flat River flows and Cane Creek flows, can be used to provide the required inflow data for the planning and operation of the OWASA system in the future.

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APPENDIX A

Correlation of Monthly Cane Creek Inflows to Monthly Flat River Flows

Regression of Cane Creek Monthly Inflows on a Constant, Flat River Monthly Flows, and Dummy Variables Measuring the Shifts in Both the Constant Term and the Slope Coefficient Between Seasons

Data Period: Oct. '60 - Sept. '61, Oct. '62 - Sept. '67, Oct. '68 - Sept. '73

Dry Season: August, September, and October

CC = Monthly Cane Creek Inflows (in cfs-month)
FR = Monthly Flat River Discharges (in cfs-month)

DUMMY1 = 1 for the dry months of August, September, and October
DUMMY1 = 0 for the wet months of January-July, November and December

DUMMY2 = FR for the dry months of August, September, and October
DUMMY2 = 0 for the wet months of January-July, November and December

Model:

$$CC = b_0 + b_1 \cdot DUMMY1 + b_2 \cdot FR + b_3 \cdot DUMMY2$$

Results: Ordinary Least Squares

Dependent Variable	CC	Number of Observation	144
Mean of Dep. Variable	894.2143	Std. Dev. of Dep. Var.	969.203996
Durbin Watson statistic	1.6706	Estimated Autocorrelation	0.16469
Std. Error of Regr.	492.7660	Sum of Squared Residuals	0.339946E+08
Total Variation	0.13433E+09	Regression Variation	0.10033E+09
Regression degrees of freedom	3	Residual degrees of freedom	140
R - squared	0.74693	Adjusted R - squared	0.74151
F(3, 140)	137.7345	Prob. Value for F	0.00000

Variable	Coefficient	Std. Error	t-ratio	Prob|t|>x	Mean of X	Std.Dev.of X
Constant	56.8874	74.44	.764	.44604		
DUMMY1	21.1498	121.7	.174	.86228	.25000	.43452
FR	.237566	.1319E-01	18.006	.00000	3798.74989	3710.96255
DUMMY2	-.131232	.2687E-01	-4.884	.00000	536.57021	1992.34735

At the 5 % significance level, the constant and DUMMY1 are insignificant.
FR and DUMMY2 are significant.
Drop either the constant term or DUMMY1 from the model.

Drop the Constant Term

Model:

$$CC = b_1 \cdot DUMMY1 + b_2 \cdot FR + b_3 \cdot DUMMY2$$

Result: Ordinary Least Squares

```
Dependent Variable                 CC    Number of Observations             144
Mean of Dep. Variable        894.2143    Std. Dev. of Dep. Var.      969.203996
Durbin Watson statistic        1.6813    Estimated Autocorrelation      0.15937
Std. Error of Regr.          492.0386    Sum of Squared Residuals  0.341364E+08
Total Variation           0.13433E+09    Regression Variation       0.10019E+09
Regression degrees of freedom       2    Residual degrees of freedom        141
R - squared                   0.74587    Adjusted R - squared           0.74227
F( 2, 141)                   206.9202    Prob. Value for F              0.00000

Variable   Coefficient   Std. Error  t-ratio  Prob|t|>x     Mean of X    Std.Dev.of X
DUMMY1     78.0372            96.13     .812   .41828         .25000          .43452
FR          .245339      .8391E-02   29.237   .00000     3798.74989      3710.96255
DUMMY2     -.139004      .2483E-01   -5.598   .00000      536.57021      1992.34735
```

DUMMY1 is insignificant, meaning that the difference between the constant term in the dry season relationship and the constant term in the wet season relationship (which is set equal to zero in this model, i.e., $b_o = 0$) is not significantly different than zero.
DUMMY1 can also be dropped from the model.
Both FR and DUMMY2 are highly significant.

Drop DUMMY1 Initially From the Full Model, Instead of the Constant Term

Model:

$$CC = b_o + b_2 \cdot FR + b_3 \cdot DUMMY2$$

Results: Ordinary Least Squares

```
Dependent Variable                 CC    Number of Observations             144
Mean of Dep. Variable        894.2143    Std. Dev. of Dep. Var.      969.203996
Durbin Watson statistic        1.6684    Estimated Autocorrelation      0.16580
Std. Error of Regr.          491.0685    Sum of Squared Residuals  0.340019E+08
Total Variation           0.13433E+09    Regression Variation       0.10033E+09
Regression degrees of freedom       2    Residual degrees of freedom        141
R - squared                   0.74687    Adjusted R - squared           0.74328
F( 2, 141)                   208.0174    Prob. Value for F              0.00000
```

Variable	Coefficient	Std. Error	t-ratio	Prob|t|>x	Mean of X	Std.Dev.of X
Constant	64.8011	58.69	1.104	.27139		
FR	.236485	.1159E-01	20.396	.00000	3798.74989	3710.96255
DUMMY2	-.128472	.2160E-01	-5.949	.00000	536.57021	1992.34735

At the 5 % significance level, the constant term is insignificant, while the variables FR and DUMMY2 remain highly significant. The constant term can be dropped from this model.

Thus, both the constant term and DUMMY1 can be dropped from the full model.

Drop the Constant Term and DUMMY1 as Explanatory Variables

Model:

$$CC = b_2 \cdot FR + b_3 \cdot DUMMY2$$

Results: Ordinary Least Squares

Dependent Variable	CC	Number of Observations	144
Mean of Dep. Variable	894.2143	Std. Dev. of Dep. Var.	969.203996
Durbin Watson statistic	1.6728	Estimated Autocorrelation	0.16361
Std. Error of Regr.	491.4474	Sum of Squared Residuals	0.342959E+08
Total Variation	0.13433E+09	Regression Variation	0.10003E+09
Regression degrees of freedom	1	Residual degrees of freedom	142
R - squared	0.74469	Adjusted R - squared	0.74289
F(1, 142)	414.1761	Prob. Value for F	0.00000

Variable	Coefficient	Std. Error	t-ratio	Prob|t|>x	Mean of X	Std.Dev.of X
FR	.245339	.8381E-02	29.272	.00000	3798.74989	3710.96255
DUMMY2	-.129105	.2160E-01	-5.976	.00000	536.57021	1992.34735

The final relationships are:

CC = 0.245339*FR	for the wet months of January-July, November, and December
CC = 0.116234*FR	for the dry months of August, September, and October

APPENDIX B

Safe Yield Results for the Expansion of Stone Quarry with Various Cane Creek and University Lake Working Volumes

In this analysis, the working volumes considered for UL were 100, 200, 300, 400, 500, and 600 MG. The working volumes of CC included in the study were 700, 1000, 1500, 2000, 2500, and 3000 MG. The safe yield function with an expanding Stone Quarry was evaluated for all combinations of these working volumes. Only the historical inflow data of Set 1A was used because it was considered to be the most reliable and, as described in section 3.4.2, the system safe yield was found to be insensitive to inflow conditions for the trial Stone Quarry volumes considered.

Table B.1 through Table B.6 report the safe yield values for a given University Lake working volume. For example, Table B.1 contains the estimates of the reliable yield from the existing OWASA system as Stone Quarry expands for each of the combinations of a University Lake working volume equal to 100 MG and the six Cane Creek working volumes considered. Table B.2 is for a UL working volume of 200 MG. Table B.3 is for a UL working volume equal to 300 MG, and so on. Figure B.1 through Figure B.6 graphically represent the data of the corresponding table.

Table B.1

Safe Yield in MGD

Universtiy Lake Working Volume = 100 MG

Stone Quarry Working Volume (MG)	Cane Creek Working Volume (M G)					
	700	1000	1500	2000	2500	3000
0	7.76	9.76	12.34	14.72	17.03	19.11
50	8.09	10.09	12.58	14.96	17.24	19.32
100	8.43	10.43	12.82	15.20	17.44	19.53
150	8.76	10.68	13.06	15.44	17.65	19.74
200	9.09	10.91	13.29	15.68	17.86	19.94
250	9.43	11.15	13.53	15.91	18.07	20.15
300	9.76	11.39	13.77	16.15	18.28	20.36
350	10.09	11.63	14.01	16.39	18.49	20.57
400	10.43	11.87	14.25	16.61	18.69	20.78
450	10.68	12.10	14.48	16.82	18.90	20.99
500	10.91	12.34	14.72	17.03	19.11	21.19
600	11.39	12.82	15.20	17.44	19.53	21.61
700	11.87	13.29	15.68	17.86	19.94	21.79
800	12.34	13.77	16.15	18.28	20.36	21.86
900	12.82	14.25	16.61	18.69	20.78	21.94
1000	13.29	14.72	17.03	19.11	21.19	22.01
1200	14.25	15.68	17.86	19.94	21.79	22.15
1400	15.20	16.61	18.69	20.78	21.94	22.30
1600	16.15	17.44	19.53	21.61	22.08	22.44
1800	17.03	18.28	20.36	21.86	22.22	22.57
2000	17.86	19.11	21.19	22.01	22.37	22.71
2200	18.69	19.94	21.79	22.15	22.50	22.85
2400	19.53	20.78	21.94	22.30	22.64	22.99
2600	20.36	21.61	22.08	22.44	22.78	23.13
2800	21.19	21.86	22.22	22.57	22.92	23.26
3000	21.79	22.01	22.37	22.71	23.06	23.40

Figure B.1
Safe Yield with the Expansion of SQ
University Lake Capacity = 100 MG

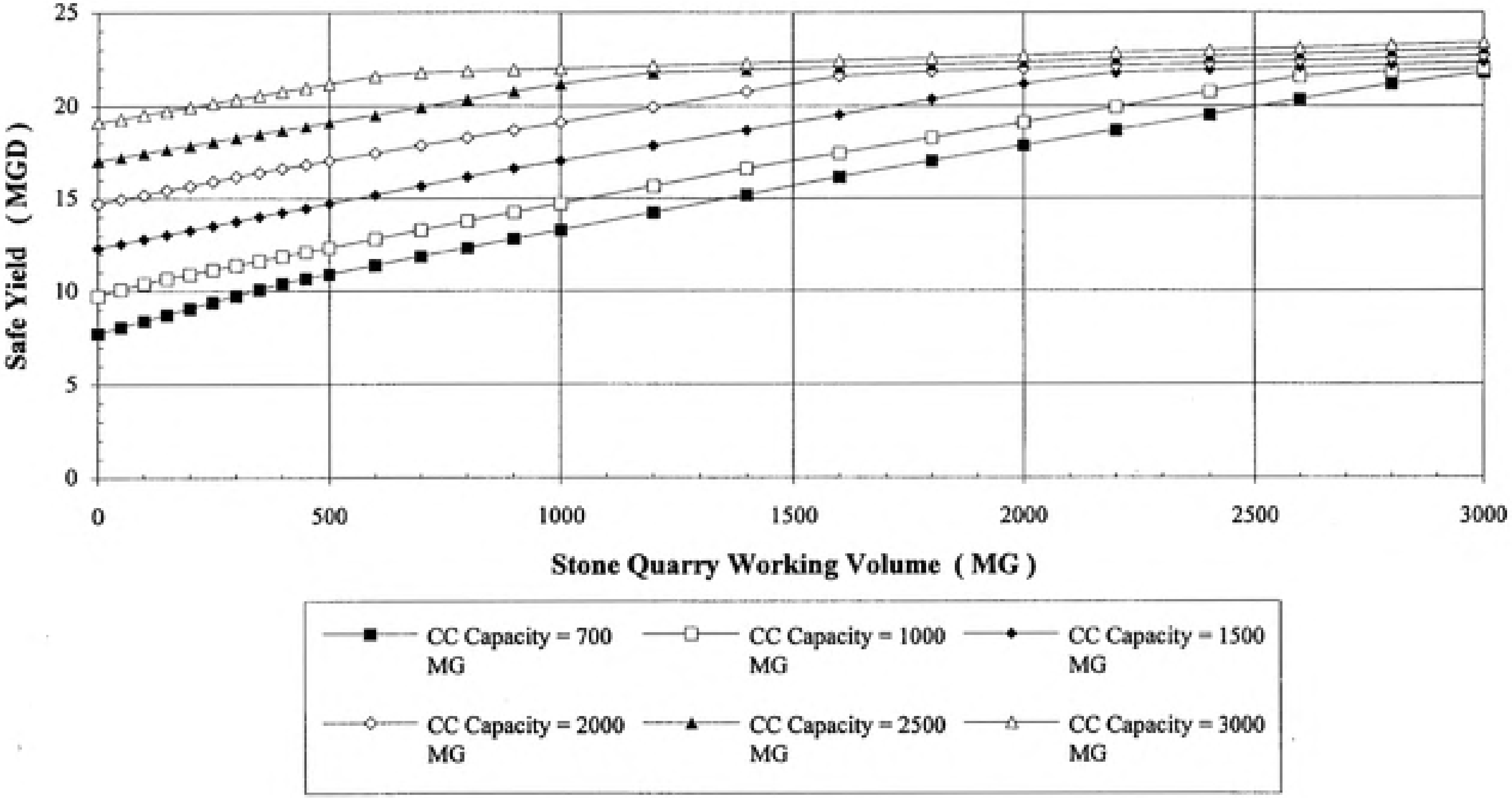


Table B.2

Safe Yield in MGD

University Lake Working Volume = 200 MG

Stone Quarry Working Volume (MG)	Cane Creek Working Volume (M G)					
	700	1000	1500	2000	2500	3000
0	8.43	10.43	12.82	15.20	17.44	19.53
50	8.76	10.68	13.06	15.44	17.65	19.74
100	9.09	10.91	13.29	15.68	17.86	19.94
150	9.43	11.15	13.53	15.91	18.07	20.15
200	9.76	11.39	13.77	16.15	18.28	20.36
250	10.09	11.63	14.01	16.39	18.49	20.57
300	10.43	11.87	14.25	16.61	18.69	20.78
350	10.68	12.10	14.48	16.82	18.90	20.99
400	10.91	12.34	14.72	17.03	19.11	21.19
450	11.15	12.58	14.96	17.24	19.32	21.40
500	11.39	12.82	15.20	17.44	19.53	21.61
600	11.87	13.29	15.68	17.86	19.94	22.03
700	12.34	13.77	16.15	18.28	20.36	22.18
800	12.82	14.25	16.61	18.69	20.78	22.25
900	13.29	14.72	17.03	19.11	21.19	22.32
1000	13.77	15.20	17.44	19.53	21.61	22.38
1200	14.72	16.15	18.28	20.36	22.18	22.52
1400	15.68	17.03	19.11	21.19	22.32	22.65
1600	16.61	17.86	19.94	22.03	22.45	22.79
1800	17.44	18.69	20.78	22.25	22.59	22.92
2000	18.28	19.53	21.61	22.38	22.73	23.05
2200	19.11	20.36	22.18	22.52	22.85	23.18
2400	19.94	21.19	22.32	22.65	22.99	23.30
2600	20.78	22.03	22.45	22.79	23.11	23.42
2800	21.61	22.25	22.59	22.92	23.24	23.55
3000	22.18	22.38	22.73	23.05	23.36	23.67

Figure B.2
Safe Yield with the Expansion of SQ
University Lake Capacity = 200 MG

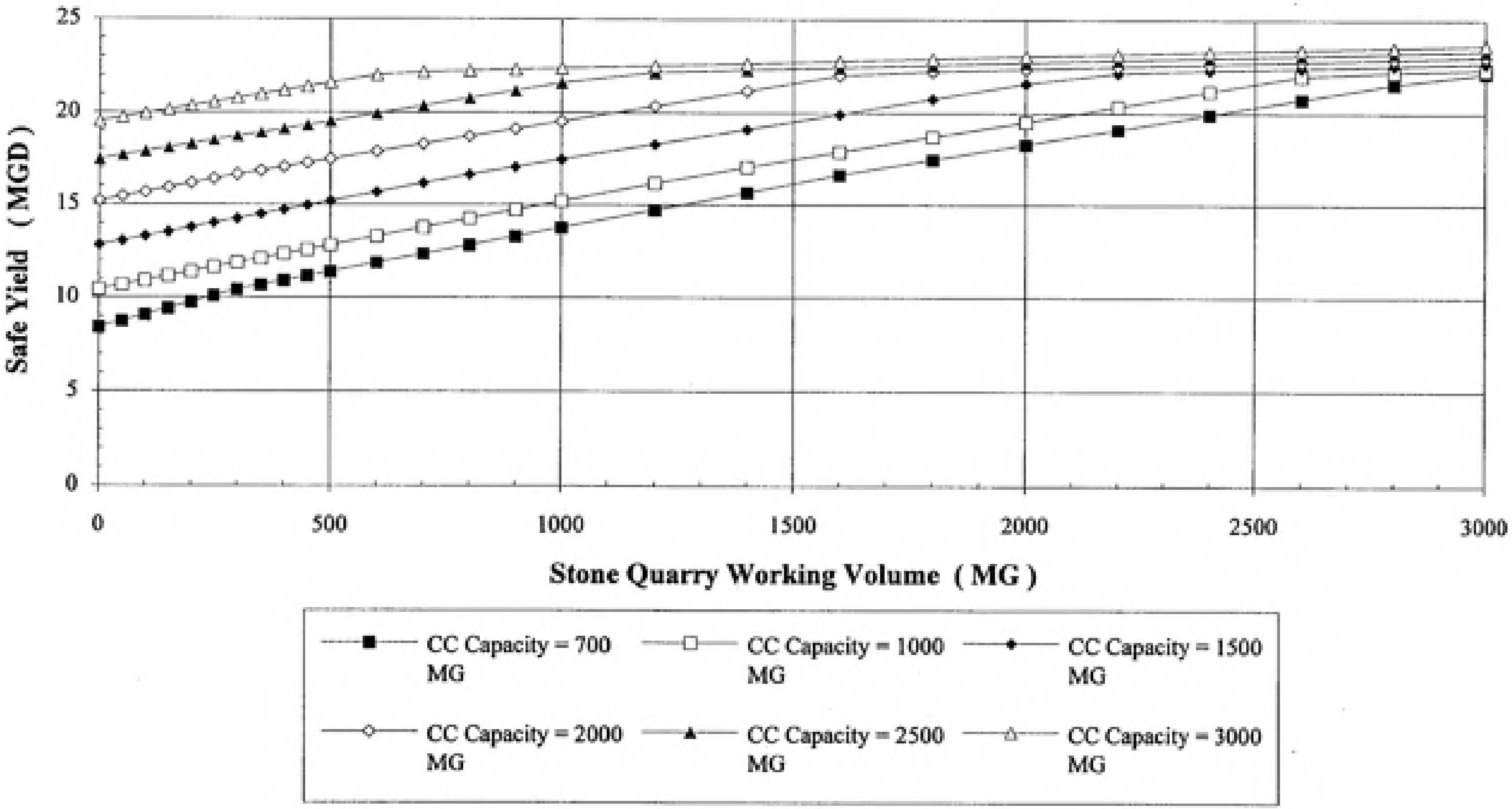


Table B.3

Safe Yield in MGD
University Lake Working Volume = 300 MG

Stone Quarry Working Volume (MG)	Cane Creek Working Volume (M G)					
	700	1000	1500	2000	2500	3000
0	9.09	10.91	13.29	15.68	17.86	19.94
50	9.43	11.15	13.53	15.91	18.07	20.15
100	9.76	11.39	13.77	16.15	18.28	20.36
150	10.09	11.63	14.01	16.39	18.49	20.57
200	10.43	11.87	14.25	16.61	18.69	20.78
250	10.68	12.10	14.48	16.82	18.90	20.99
300	10.91	12.34	14.72	17.03	19.11	21.19
350	11.15	12.58	14.96	17.24	19.32	21.40
400	11.39	12.82	15.20	17.44	19.53	21.61
450	11.63	13.06	15.44	17.65	19.74	21.82
500	11.87	13.29	15.68	17.86	19.94	22.03
600	12.34	13.77	16.15	18.28	20.36	22.31
700	12.82	14.25	16.61	18.69	20.78	22.38
800	13.29	14.72	17.03	19.11	21.19	22.44
900	13.77	15.20	17.44	19.53	21.61	22.50
1000	14.25	15.68	17.86	19.94	22.03	22.56
1200	15.20	16.61	18.69	20.78	22.38	22.68
1400	16.15	17.44	19.53	21.61	22.50	22.81
1600	17.03	18.28	20.36	22.31	22.62	22.93
1800	17.86	19.11	21.19	22.44	22.75	23.05
2000	18.69	19.94	22.03	22.56	22.87	23.18
2200	19.53	20.78	22.38	22.68	22.99	23.30
2400	20.36	21.61	22.50	22.81	23.12	23.42
2600	21.19	22.31	22.62	22.93	23.24	23.55
2800	22.03	22.44	22.75	23.05	23.36	23.67
3000	22.38	22.56	22.87	23.18	23.49	23.79

Figure B.3
Safe Yield with the Expansion of SQ
University Lake Capacity = 300 MG

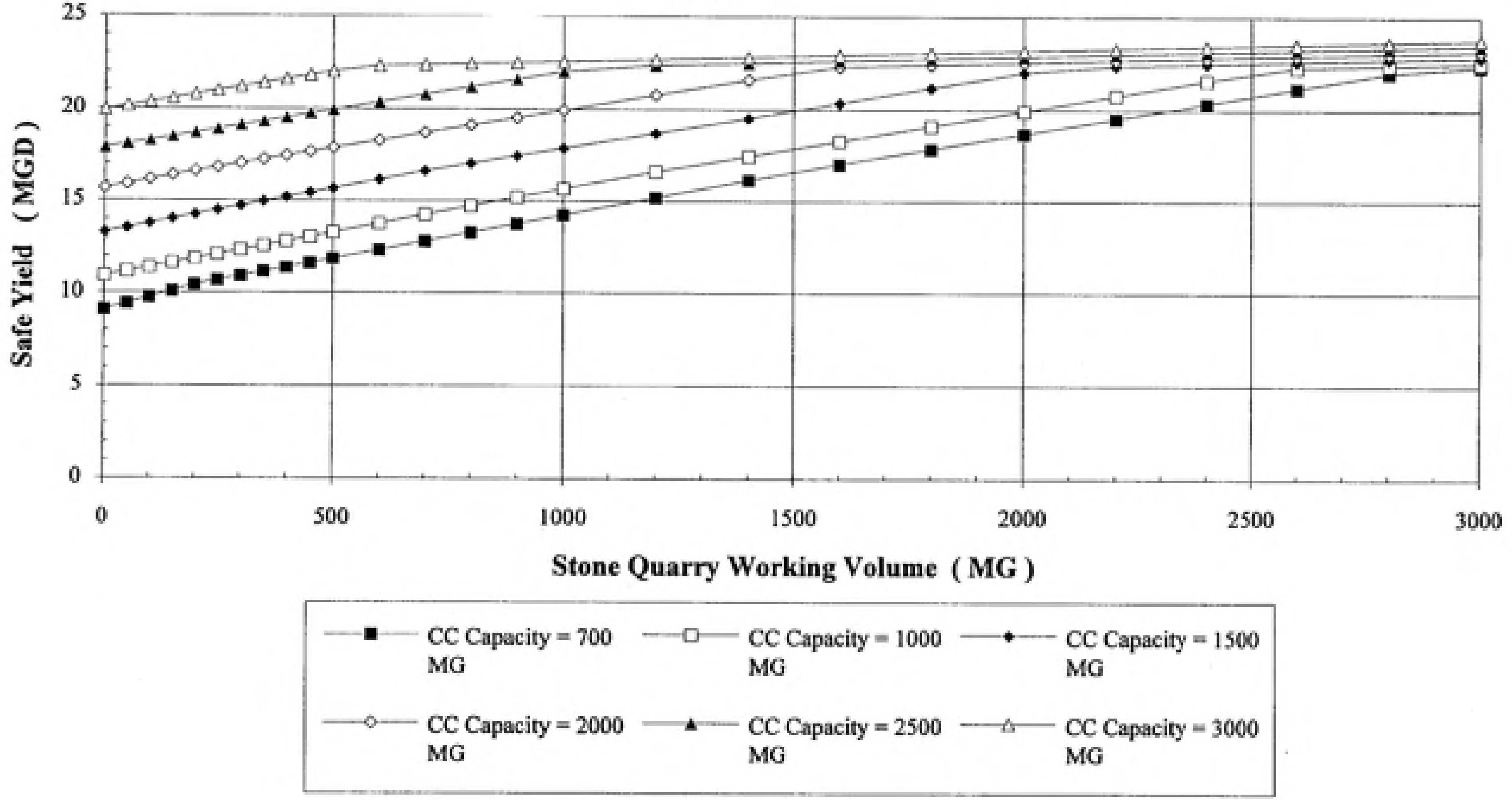


Table B.4

Safe Yield in MGD

University Lake Capacity at 400 MG

Stone Quarry Working Volume (MG)	Cane Creek Working Volume (M G)					
	700	1000	1500	2000	2500	3000
0	9.76	11.39	13.77	16.15	18.28	20.36
50	10.09	11.63	14.01	16.39	18.49	20.57
100	10.43	11.87	14.25	16.61	18.69	20.78
150	10.68	12.10	14.48	16.82	18.90	20.99
200	10.91	12.34	14.72	17.03	19.11	21.19
250	11.15	12.58	14.96	17.24	19.32	21.40
300	11.39	12.82	15.20	17.44	19.53	21.61
350	11.63	13.06	15.44	17.65	19.74	21.82
400	11.87	13.29	15.68	17.86	19.94	22.03
450	12.10	13.53	15.91	18.07	20.15	22.24
500	12.34	13.77	16.15	18.28	20.36	22.38
600	12.82	14.25	16.61	18.69	20.78	22.44
700	13.29	14.72	17.03	19.11	21.19	22.50
800	13.77	15.20	17.44	19.53	21.61	22.56
900	14.25	15.68	17.86	19.94	22.03	22.62
1000	14.72	16.15	18.28	20.36	22.38	22.68
1200	15.68	17.03	19.11	21.19	22.50	22.81
1400	16.61	17.86	19.94	22.03	22.62	22.93
1600	17.44	18.69	20.78	22.44	22.75	23.05
1800	18.28	19.53	21.61	22.56	22.87	23.18
2000	19.11	20.36	22.38	22.68	22.99	23.30
2200	19.94	21.19	22.50	22.81	23.12	23.42
2400	20.78	22.03	22.62	22.93	23.24	23.55
2600	21.61	22.44	22.75	23.05	23.36	23.67
2800	22.38	22.56	22.87	23.18	23.49	23.79
3000	22.50	22.68	22.99	23.30	23.61	23.92

Figure B.4
Safe Yield with the Expansion of SQ
University Lake Capacity = 400 MG

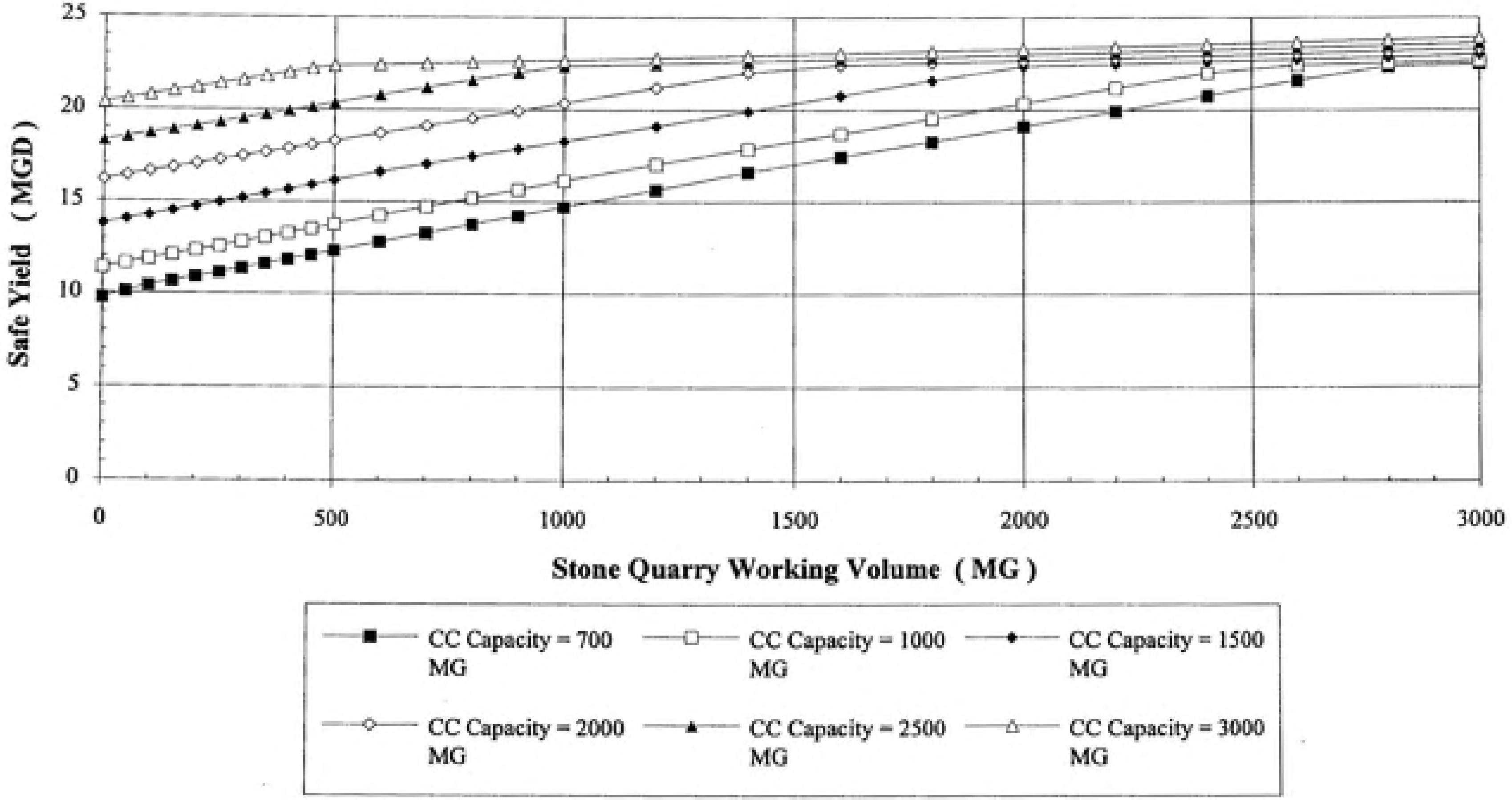


Table B.5

Safe Yield in MGD

University Lake Working Volume = 500 MG

Stone Quarry Working Volume (MG)	Cane Creek Working Volume (M G)					
	700	1000	1500	2000	2500	3000
0	10.43	11.87	14.25	16.61	18.69	20.78
50	10.68	12.10	14.48	16.82	18.90	20.99
100	10.91	12.34	14.72	17.03	19.11	21.19
150	11.15	12.58	14.96	17.24	19.32	21.40
200	11.39	12.82	15.20	17.44	19.53	21.61
250	11.63	13.06	15.44	17.65	19.74	21.82
300	11.87	13.29	15.68	17.86	19.94	22.03
350	12.10	13.53	15.91	18.07	20.15	22.24
400	12.34	13.77	16.15	18.28	20.36	22.43
450	12.58	14.01	16.39	18.49	20.57	22.50
500	12.82	14.25	16.61	18.69	20.78	22.50
600	13.29	14.72	17.03	19.11	21.19	22.56
700	13.77	15.20	17.44	19.53	21.61	22.62
800	14.25	15.68	17.86	19.94	22.03	22.68
900	14.72	16.15	18.28	20.36	22.43	22.75
1000	15.20	16.61	18.69	20.78	22.50	22.81
1200	16.15	17.44	19.53	21.61	22.62	22.93
1400	17.03	18.28	20.36	22.43	22.75	23.05
1600	17.86	19.11	21.19	22.56	22.87	23.18
1800	18.69	19.94	22.03	22.68	22.99	23.30
2000	19.53	20.78	22.50	22.81	23.12	23.42
2200	20.36	21.61	22.62	22.93	23.24	23.54
2400	21.19	22.43	22.75	23.05	23.36	23.66
2600	22.03	22.56	22.87	23.18	23.48	23.78
2800	22.50	22.68	22.99	23.30	23.60	23.89
3000	22.62	22.81	23.12	23.42	23.72	24.01

Figure B.5
Safe Yield with the Expansion of SQ
University Lake Capacity = 500 MG

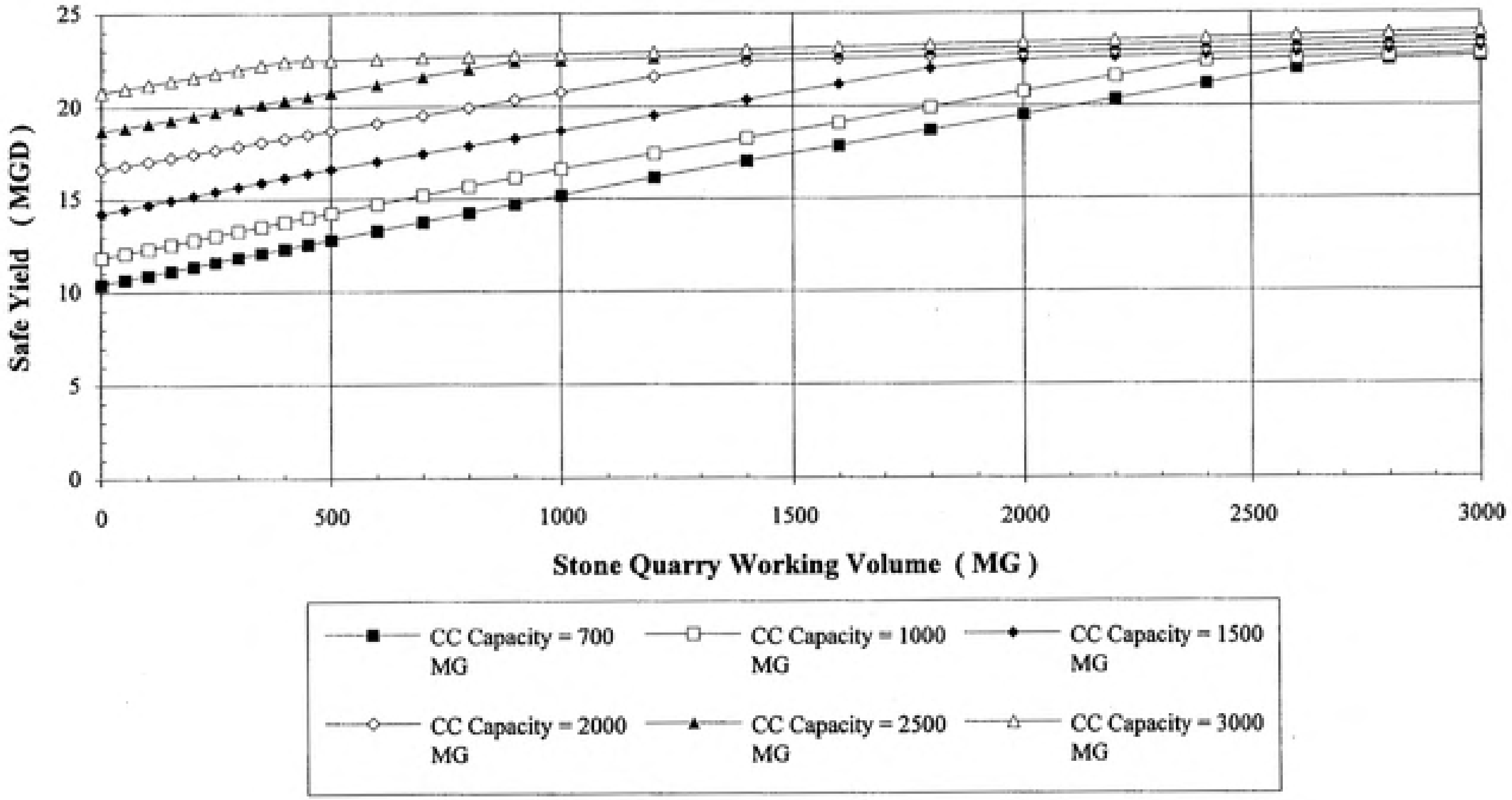
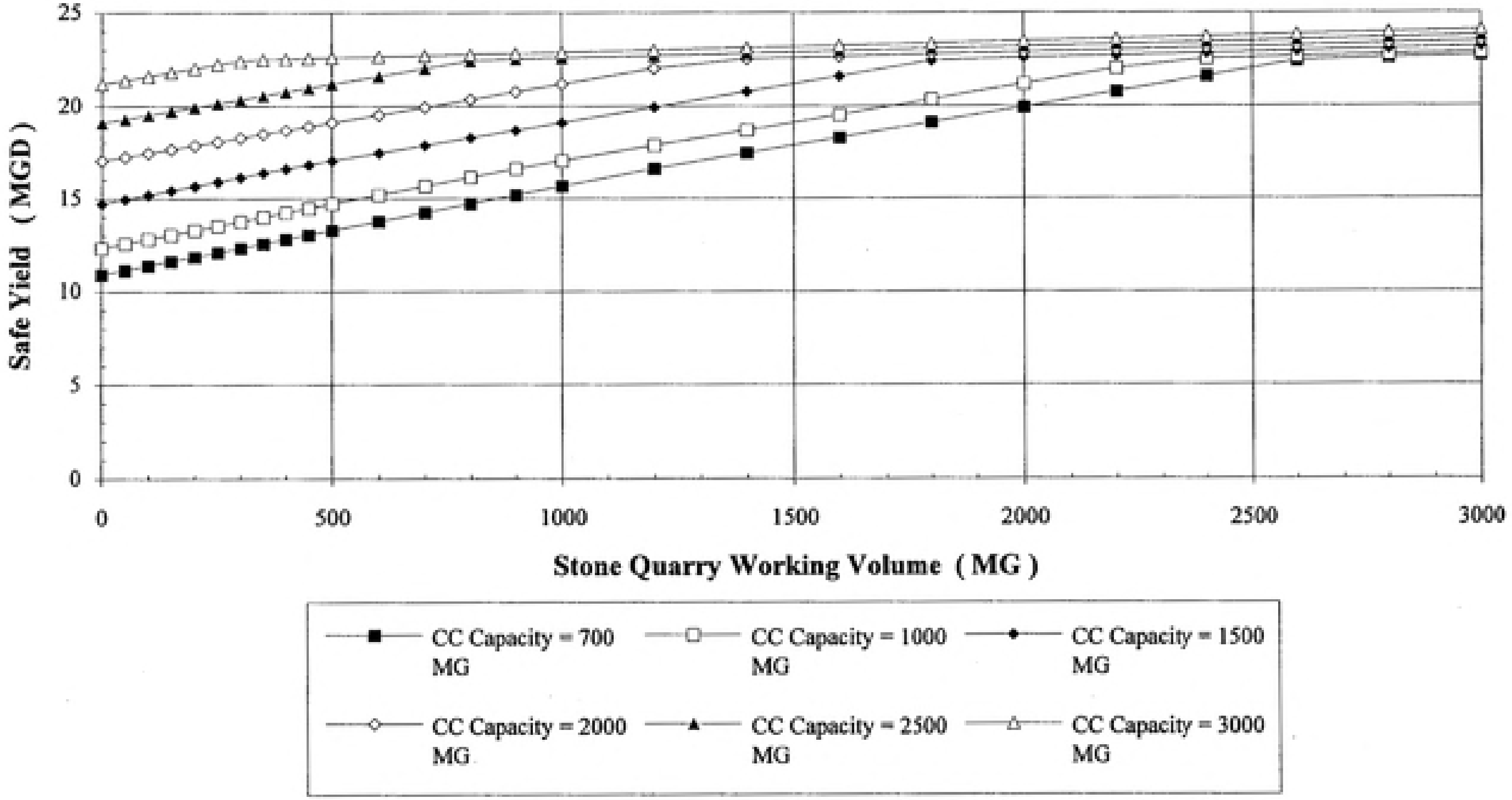


Table B.6

Safe Yield in MGD
University Lake Working Volume = 600 MG

Stone Quarry Working Volume (MG)	Cane Creek Working Volume (M G)					
	700	1000	1500	2000	2500	3000
0	10.91	12.34	14.72	17.03	19.11	21.19
50	11.15	12.58	14.96	17.24	19.32	21.40
100	11.39	12.82	15.20	17.44	19.53	21.61
150	11.63	13.06	15.44	17.65	19.74	21.82
200	11.87	13.29	15.68	17.86	19.94	22.03
250	12.10	13.53	15.91	18.07	20.15	22.24
300	12.34	13.77	16.15	18.28	20.36	22.43
350	12.58	14.01	16.39	18.49	20.57	22.50
400	12.82	14.25	16.61	18.69	20.78	22.53
450	13.06	14.48	16.82	18.90	20.99	22.56
500	13.29	14.72	17.03	19.11	21.19	22.59
600	13.77	15.20	17.44	19.53	21.61	22.64
700	14.25	15.68	17.86	19.94	22.03	22.70
800	14.72	16.15	18.28	20.36	22.43	22.76
900	15.20	16.61	18.69	20.78	22.53	22.82
1000	15.68	17.03	19.11	21.19	22.59	22.88
1200	16.61	17.86	19.94	22.03	22.70	23.00
1400	17.44	18.69	20.78	22.53	22.82	23.12
1600	18.28	19.53	21.61	22.64	22.94	23.24
1800	19.11	20.36	22.43	22.76	23.06	23.36
2000	19.94	21.19	22.59	22.88	23.18	23.48
2200	20.78	22.03	22.70	23.00	23.30	23.60
2400	21.61	22.53	22.82	23.12	23.42	23.72
2600	22.43	22.64	22.94	23.24	23.54	23.84
2800	22.59	22.76	23.06	23.36	23.66	23.95
3000	22.70	22.88	23.18	23.48	23.78	24.07

Figure B.6
Safe Yield with the Expansion of SQ
University Lake Capacity = 600 MG



Minimum Attractive Rate of Return = 10 %

Inflation factor = 2 %

LINEAR DEMAND PROJECTIONS

Year 2031 is the datum and Present Values are calculated to that year

Scenario 1 Implementation of JL by 2031

Inflated Capital Costs of JL construction: ($ 19M)*$(1.02)^{40}$ = $ 41.95 M

Total P.V. Cost in 2031 = $ 41.95 M

Scenario 2 SQ Expanded to 1000 MG by 2031
Increases Capacity to 17.6 MGD
Extends Excess Capacity to year 2051
Implement JL by 2051
Delays JL 20 years

P.V. in 2031 of keeping JL option open for 20 years = ($20,000/yr)*(8.514) = $170,280

P.V. in 2031 of land payments for buffering land = ($35,000/yr)*(8.514)*$(1.1)^{37}$
= $ 10.13 M

P.V. in 2031 of JL construction costs in 2051 = ($ 19M)*$(1.02)^{60}$*(1/$(1.1)^{20}$)
= $ 9.27 M

Total P.V. Costs in 2031 = $ 19.57 M

Scenario 3 SQ Expanded to 3000 MG by 2031
Increases Capacity to 22.9 MGD
Extends Excess Capacity to 2081
Implement JL by 2081
Delays JL by 50 years

P.V. in 2031 of keeping JL option open for 50 years = ($20,000/yr)*(9.915) = $198,300

P.V. in 2031 of land payments for buffering land = ($35,000/yr)*(8.514)*$(1.1)^{37}$
= $ 9.27 M

P.V. in 2031 of JL construction costs in 2081 = ($ 19M)*$(1.02)^{90}$*(1/$(1.1)^{50}$)
= $ 0.96 M

Total P.V. Costs in 2031 = $ 10.43 M

GEOMETRIC DEMAND PROJECTIONS

Year 2020 is the datum for comparison
Present Values are calculated to that year

Scenario 1 Construction of JL in 2020

Inflated Capital Costs of JL construction: ($ 19M)*$(1.02)^{29}$ = $ 33.74 M

Total P.V. Cost in 2020 = $ 33.74 M

Scenario 2 SQ Expanded to 1000 MG by 2020
Increases Capacity to 17.6 MGD
Extends Excess Capacity to year 2029
Implement JL by 2029
Delays JL 9 years

P.V. in 2020 of keeping JL option open for 9 years = ($20,000/yr)*(5.759) = $115,200

P.V. in 2020 of land payments for buffering land = ($35,000/yr)*(8.514)*$(1.1)^{26}$
= $ 3.55 M

P.V. in 2020 of JL construction costs in 2029 = ($ 19M)*$(1.02)^{38}*(1/(1.1)^{9})$
= $ 17.10 M

Total P.V. Costs in 2020 = $ 20.77 M

Scenario 3 SQ Expanded to 2150 MG by 2020
Increases Capacity to 22.4 MGD
Extends Excess Capacity to 2039
Implement JL by 2039
Delays JL by 19 years

P.V. in 2020 of keeping JL option open for 19 years = ($20,000/yr)*(8.365) = $167,300

P.V. in 2020 of land payments for buffering land = ($35,000/yr)*(8.514)*$(1.1)^{26}$
= $ 3.55 M

P.V. in 2020 of JL construction costs in 2039 = ($ 19M)*$(1.02)^{48}*(1/(1.1)^{19})$
= $ 8.04 M

Total P.V. Costs in 2020 = $ 11.76 M