ABSTRACT

ANGELIQUE M. NELSON. Assessment Of OWASA's Water Rationing Policy Using A Linear Programming Model. (Under The Direction of Dr. DONALD LAURIA)

OWASA adopted its first rationing policy in July 1977 and revised it in October 1984. The rationing policy is based upon the amount of water stored in University Lake. The years 1985 through 1988 were very dry, with low inflows to University Lake. Consequently, OWASA was forced to invoke a great deal of rationing during these years. These circumstances provided a case for developing a linear programming model in this report for determining the optimal amount of rationing.

The linear programming model was formulated using amounts of water in storage in University Lake at the end of each month, shortfalls in meeting demands each month, and excess spillages from the reservoir each month as unknown decision variables. Constraints on continuity, maximum demand reduction due to rationing, maximum reservoir capacity, and desirable target volumes to have in storage were included in the model. Parameters such as inflows, demands, and demand reductions via rationing were evaluated from historical data.

A set of input parameters was chosen for a baseline solution, which was used to compare OWASA's historical operation with the optimization model. From the results, the OWASA rationing policy appears to be too simplistic; it is probably insufficient to minimize the amount of required rationing by using a policy that is based only on the amount of water in storage. A more sophisticated policy is needed and a model such as the one developed in this report could provide a means for constructing a more effective policy.

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CHAPTER 1. INTRODUCTION

1.1 Motivation

The Orange Water and Sewer Authority (OWASA) has owned and operated the water supply for the Towns of Chapel Hill and Carrboro, North Carolina since February 1977, when it was purchased from the University of North Carolina. OWASA adopted their first rationing policy in July, 1977. This policy was revised in October 1984 and is still in place today. The rationing policy was set in place before OWASA constructed Cane Creek Reservoir, a much needed additional source of water that has made rationing unnecessary in recent years and probably for some years into the future. The years 1985 through 1988 were very dry, with low inflows to University Lake, the main water source at the time and the source on which the rationing policy is based. Consequently, OWASA was forced to invoke a great deal of rationing during the years 1985 through 1988.

It is uncertain how well OWASA's rationing rule performs. For example, does it require excessive rationing? How well does it assist OWASA in meeting future demands? In light of the fact that we have the advantage of hindsight, we are now in a position to test the OWASA policy to determine its effectiveness using a linear programming model, developed herein. The model is designed to minimize the total amount of required rationing, subject to constraints on meeting the reduced demands associated with rationing. This test is comprised of a comparison of the amounts of rationing needed using OWASA's rule versus the amounts of required rationing that the results of the linear programming model suggest.

1.2 Objectives

The first objective of this technical report is to develop a linear programming model that minimizes the amount of rationing for the OWASA system. Mathematical optimization is capable of handling such a complex problem, and it allows for both present and future uses of the model to assist a water authority in making rationing decisions.

The second objective of this report is to apply the linear programming model to the actual events that OWASA encountered during the years 1985-1988. In order to do this, the actual input parameters required to run the model need to be determined and introduced into the model. These parameters include items such as the inflows to University Lake, the demands needed to be met, and the maximum and minimum storage capacities of University Lake. Most of these data can be obtained from OWASA's historical records, although some will have to be calculated.

The final objective is to illustrate how the linear programming model can assist in the formulation of rationing policies *ex ante* rather than *ex post facto* . This objective can be accomplished by using the model in two different ways. The first is a chance constrained approach that focuses on inflows that are known to be exceeded with a certain probability. The second is an expected-value approach that results in determining an expected value for rationing in each month of the year. The possible *ex ante* uses of the model could be helpful in assisting any water authority in making important decisions regarding rationing, not just OWASA.

1.3 Organization

The report examines the OWASA system in Chapter 2. This chapter includes the system configuration during 1985-1988 in Section 2.1, inflows to the system in Section

2.2, and the demands to be met during this time period in Section 2.3. Section 2.4 discusses the estimation of demand reduction that results from imposing rationing, the working volume of the reservoir is calculated in Section 2.5, and Section 2.6 presents a simulation performed to confirm the parameter values needed to run the linear programming model.

Chapter 3 describes the linear programming model. Section 3.1 presents an introduction to the model. Section 3.2 presents the basic linear programming parametric model, Section 3.3 describes the expanded parametric model, and Section 3.4 introduces the parameter values. Section 3.5 presents the basic linear programming baseline solution, and Section 3.6 presents the expanded model baseline solution. Section 3.7 presents sensitivity analyses.

The uses of the model in formulating *ex ante* rationing policies are investigated in Chapter 4. Section 4.1 is an introduction to the applications of the model under different rationing policies. Section 4.2 presents the chance constrained approach for using the model, and the expected-value approach is discussed in Section 4.3.

The final chapter, Chapter 5, includes a discussion of the results and the conclusions that can be drawn from them. Section 5.1 discusses the *ex post* and *ex ante* applications of the model. Section 5.2 presents an assessment of the OWASA rationing policy and Section 5.3 concludes the paper with a discussion of several modifications that could be made to the model.

CHAPTER 2. OWASA SYSTEM -- 1985 - 1988

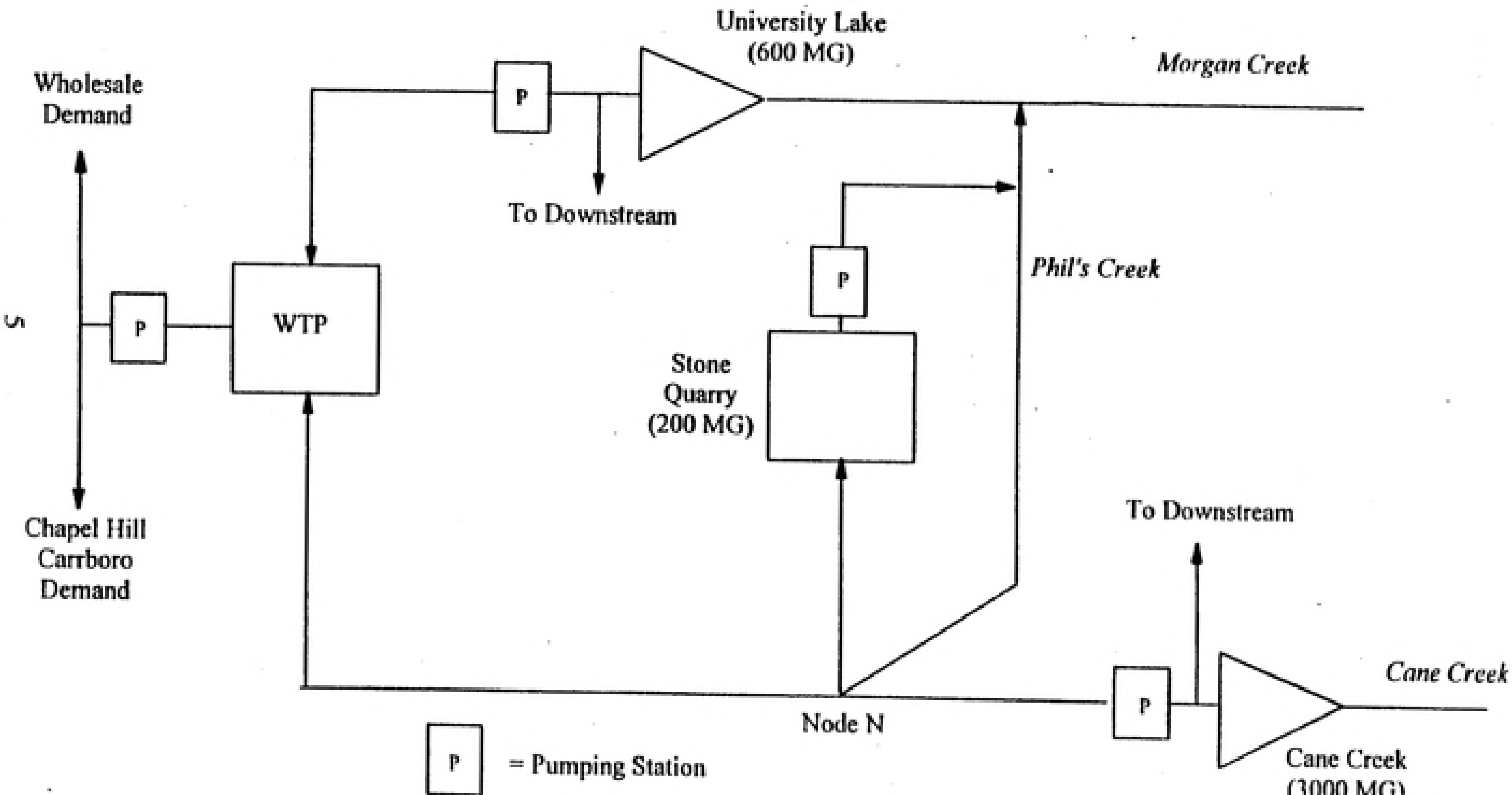
2.1 System Configuration

The OWASA system was relatively simple during the years that this report focuses on, 1985-1988. However, it has recently become much more complex. The OWASA system is presently comprised of three reservoirs: University Lake, Stone Quarry, and Cane Creek. Cane Creek has a total storage capacity of approximately 3 billion gallons. It was not completed until 1989 and is currently used only when the University Lake supply becomes low. The Stone Quarry is used for storing water pumped from the Cane Creek Reservoir, mainly in emergency situations. University Lake has a total storage capacity of about 571 million gallons (MG) and a drainage area of approximately 27 square miles. The total storage capacity of University Lake cannot all be used to meet demands. Instead, the working volume of the reservoir, which is determined in Section 2.5, is what is critical in meeting demand. The working volume of a reservoir is the total amount of storage capacity that can be used at any given time. Due to the facts that neither Cane Creek nor Stone Quarry were a significant contributor to the water supply between 1985 and 1988 and that the rationing policy is based upon the storage level in University Lake, this report focuses only on the parameters dealing with University Lake. A schematic diagram of the OWASA system is shown in Figure 2.1.

2.2 Inflows

Inflows to a reservoir are normally measured using a gauge that records the amount of flow over a given period of time. In the case of University Lake, there is no gauging station that directly measures the inflows to the reservoir. When inflows cannot be directly measured, they are usually estimated, or predicted, using flow measurements from

Figure 2.1
Schematic of OWASA System



a gauging station for a similar system. Inflows to University Lake can be estimated using the historical inflow data at a gauging station with a close correlation to the reservoir in question. Originally, the historical flows at the Cane Creek near Teer gauging station were used. However, these data were only available for the 14-year period 1959 to 1973 and this may not be a sufficient period of time to cover a wide range of inflow conditions. Therefore, a surrogate gauging station with a longer historical record is needed. In a report completed for OWASA by Speight (1994) statistical regressions were performed on streamflow data from 15 different gauging stations, in the Neuse River basin, the Pee Dee River basin, and the Cape Fear River basin, to determine correlations with the Cane Creek near Teer data. The total annual flow into each gauging station during the 14-year period coinciding with data from Cane Creek near Teer station, 1959 to 1973, was used in the analysis. The historical data from the Flat River at Bahama gauge were found to be most highly correlated with the Cane Creek near Teer data based on the R-squared values resulting from the regression analysis.

Once Flat River at Bahama was chosen as the surrogate, the monthly data were regressed using the least squares method in order to obtain a predictive model for monthly inflows to Cane Creek Reservoir. A general model to investigate the effect of seasonal variations in flows was proposed and fitted using dummy variables representing dry and wet seasons. The first model looked at the effect of the seasonal dummy variable on both the intercept and slope of the relationship:

$$CC = B0 + B1 * Summer + B2 * FR + B3 * (Summer \cdot FR)$$

where: CC = monthly inflow from Cane Creek near Teer, in cfs·month

Summer = 1, for August, September, and October
= 0, for November, December and January through July

FR = monthly inflow from Flat River at Bahama, in cfs·month

Bi = regression coefficient

(Summer·FR) = the shift in the monthly inflow from Flat River at Bahama due to summer variation in flows

These results, which are shown in Appendix B, show that the constant term and the dummy variable, Summer, are not statistically significant at the 95% confidence level. Thus they were excluded from the model and the regression was repeated to obtain the final results. This model is:

$$CC = B2 * FR + B3 * (Summer \cdot FR)$$

Both of the coefficients are significant and the R-square value is acceptable (0.745). Thus the final model used to obtain the inflows was:

$CC = 0.245 \cdot FR$	January - July, November, December
$CC = 0.116 \cdot FR$	August, September, October

This means that each monthly inflow to Flat River at Bahama is multiplied by 0.245 in January through July, November, and December and by 0.116 in August, September, and October in order to estimate the monthly inflows to Cane Creek (Speight, 1994).

In order to run the linear programming model developed in this report, the monthly inflows to University Lake were needed. The inflows to a reservoir can be estimated by multiplying the inflows to another reservoir in a similar watershed by the ratio of the two drainage areas (Loucks, *et al* ., 1981). The ratio of the drainage areas of Cane Creek and University Lake is 0.89; therefore, to obtain the University Lake inflows, the inflows to Cane Creek were multiplied by 0.89. Four of the thirty years of estimated monthly inflows to University Lake that coincide with the years used for the model in this report (1985 - 1988) can be found in Table 2.1.

TABLE 2.1
Monthly Inflows To University Lake (MG/ month)

YEAR

MONTH	1985	1986	1987	1988
January	909.1	275.0	1366.4	770.5
February	1500.9	351.8	1672.1	558.8
March	319.8	827.1	2298.0	341.6
April	151.3	221.4	1276.0	395.0
May	138.2	119.8	319.3	187.1
June	55.5	33.2	238.8	64.8
July	104.2	35.5	254.0	23.2
August	247.0	269.8	11.1	26.5
September	35.9	18.1	40.7	28.9
October	46.9	12.6	25.5	68.6
November	2078.0	110.6	137.2	571.5
December	680.6	815.4	444.5	174.0

Section 4.2 presents the chance constrained use of the model developed herein. In this approach inflows that have a given probability of exceedance, p, are used to run the model. The inflows with a given probability of exceedance are used in each of the constraints of the model that involve inflows. These constraints, called continuity constraints, are discussed in Section 3.2.1. The continuity constraints are assigned a level of reliability so that the constraints are satisfied with a probability of p (Loucks, *et al.*, 1981; ReVelle, *et al.*, 1969). These inflows were found by fitting probability distributions to the data from Flat River at Bahama over the last 30 years (Speight, 1994). Three types of distributions were explored to describe the monthly inflows: the normal distribution, the log normal distribution, and the log Pearson type III distribution. In each case, the thirty values for each month were placed in descending order and were plotted using the Weibull formula: $p=m/(n+1)$, where p = plotting position or probability of exceedance, m = rank, and n = total number of observations.

Parameters for the three different distributions were estimated from the data traces for each month, and the goodness of fit of each distribution to the data was checked by performing a chi-square test. This test compares the predicted frequency of observations in intervals to the actual frequency of observations in the intervals. The test statistic is given by:

$$X^2 = \Sigma[(O - E)^2 / E]$$

where O = observed frequency and E = expected frequency.

On the basis of the chi-square test, the log normal distribution fit the data best and was used to predict inflow values for each month with given probabilities of exceedance. For example, the inflow to Cane Creek in January is predicted to exceed 433.4 million gallons 95 percent of the time. These values were then multiplied by 0.89 to obtain values for University Lake (e.g., the inflow to University Lake in January is more than 385.7 million gallons 95 percent of the time). The inflows to University Lake and their corresponding exceedance probabilities used in this report can be seen in Table 2.2.

The expected-value use of the model for developing a rationing policy entails running it with inflows for "wet" years, "dry" years, and "average" years, each with a probability of occurrence equal to one-third. In a report by Gutmann (1995), the thirty traces of inflow data for 1960 to 1989 were each run individually with 1994 water demands in Chapel Hill and Carrboro, NC to determine the wet, dry, and average years. The thirty years of historical inflow data were ranked from wettest to driest based on objective function values from a programming model developed by Gutmann (1995); the results are shown in Table 2.3. Ten traces were selected from these results to represent inflows with equal probabilities of occurrence, each with a probability of occurrence of one-tenth. The years selected are in bold type in Table 2.3. The corresponding inflows for these years were multiplied by 0.89 to convert them to University Lake inflows; Table 2.4 shows these values.

TABLE 2.2
Predicted Inflows To University Lake

Month	Probability of Exceedance	Adjusted Inflow (MG/month)
January	.99	361.5
	.95	385.7
	.9	407.4
	.5	602.5
February	.99	437.7
	.95	476.7
	.9	509.6
	.5	769.8
March	.99	486.2
	.95	528.3
	.9	565.7
	.5	852.1
April	.99	282.2
	.95	304.7
	.9	322.7
	.5	479.2
May	.99	174.7
	.95	183.9
	.9	190.5
	.5	277.4
June	.99	93.0
	.95	98.1
	.9	103.6
	.5	150.0
July	.99	86.9
	.95	88.9
	.9	90.9
	.5	115.6

TABLE 2.2 Continued
Predicted Inflows To University Lake

Month	Probability of Exceedance	Adjusted Inflows (MG/ month)
August	.99	33.6
	.95	34.5
	.9	35.3
	.5	45.5
September	.99	21.2
	.95	21.5
	.9	21.9
	.5	26.2
October	.99	177.4
	.95	28.7
	.9	29.2
	.5	37.1
November	.99	100.1
	.95	102.9
	.9	105.7
	.5	138.3
December	.99	206.9
	.95	222.1
	.9	217.2
	.5	347.8

TABLE 2.3

30 Years Of Inflows Sorted By Objective Function Value*

Year	Objective Function
1974	$93,102
1982	$93,118
1960	$93,119
1971	$93.122
1979	$93,122
1972	$93,130
1989	$93,148
1975	$93,160
1981	$94,525
1961	$94,578
1973	$94,677
1978	$94,714
1964	$94,896
1970	$94,993
1962	$95,011
1984	$95,115
1967	$96,434
1987	$96,472
1969	$96,491
1983	$96,560
1985	$96,767
1965	$97,360
1963	$97,394
1980	$97,890
1968	$98,168
1966	$98,222
1986	$98,275
1988	$98,292
1977	$99,084
1976	$99,863

(Adapted From Gutmann, 1995)

* The objective function value is the cost of pumping to meet 1994 demands. Hence, 1974 was the wettest year and 1976 was the driest.

TABLE 2.4

Ten Traces of Inflows To University Lake
With Equal Probabilities Of Occurrence (p = 0.1)*

Year

Month	1982	1979	1975	1973	1970	1967	1983	1963	1966	1977
Jan.	1553.8	1975.2	2539.1	1061.9	208.5	428.0	725.5	810.4	141.2	540.8
Feb.	1516.8	2645.2	1214.1	1883.5	864.0	785.7	1700.7	780.5	1469.9	267.4
Mar.	1076.7	1499.3	3904.8	2135.6	591.3	316.7	2591.3	2112.3	1026.5	919.9
Apr.	386.5	748.8	567.6	1995.1	875.3	213.1	2487.1	300.3	171.3	278.4
May	230.6	705.9	501.4	553.3	385.5	148.9	853.6	191.2	438.9	124.0
June	1562.8	552.6	182.7	560.2	151.7	485.4	324.4	87.1	94.8	45.9
July	354.6	137.2	3490.9	413.3	772.6	249.1	110.2	109.1	22.6	42.3
Aug.	449.2	81.0	97.9	489.1	65.1	38.8	11.8	81.2	103.5	6.1
Sep.	30.6	315.0	313.2	38.5	9.6	18.9	4.6	24.9	70.8	17.8
Oct.	300.1	149.2	87.6	18.2	12.9	13.8	12.8	12.5	54.6	42.0
Nov.	250.9	1305.3	260.8	54.4	482.8	31.5	216.5	555.1	84.7	209.8
Dec.	1119.0	329.8	348.8	921.6	233.3	828.2	1257.0	395.8	267.6	558.0

* The traces are ordered from wettest (1982) to driest (1977).

2.3 Demands

The historical demand data for the period 1985 - 1988 were obtained from OWASA. In order to meet demands, OWASA withdraws water from University Lake. These withdrawals from University Lake are the only historic demand data needed to run the model herein because the rationing policy is based entirely on the level of storage in University Lake at any given time. The monthly demands (*i.e.* the volumes of pumped water from University Lake for the period of concern) are shown in Table 2.5.

If the level of University Lake becomes too low, even with rationing, OWASA can purchase water from Durham, NC, or withdraw water from Stone Quarry. To account for the occasional need to obtain water from other sources, the option of purchasing water from an outside source is built into the expanded model. This is discussed further in Section 3.1.

TABLE 2.5
Water Withdrawals From
University Lake (MG / Month)

	Year			
Month	**1985**	**1986**	**1987**	**1988**
January	145.1	178.2	158.7	185.6
February	134.9	158.8	148.9	179.8
March	157.1	166.0	155.9	189.8
April	180.8	192.1	165.1	193.6
May	169.2	207.4	170.9	203.2
June	163.0	213.4	181.1	209.4
July	146.0	160.4	214.8	189.2
August	160.8	134.0	605.2	128.3
September	200.5	151.8	116.9	126.9
October	198.0	89.3	150.5	202.3
November	179.0	70.8	148.2	197.9
December	160.9	81.7	171.7	193.9

2.4 Demand Reduction Via Rationing

The purpose of this section is to estimate the amounts by which demand changed when OWASA invoked its rationing policy in the period 1985 - 1988. The dates on which OWASA invoked rationing during 1985-1988 are shown in Table 2.6. As can be seen in Appendix A, OWASA imposes rationing in stages based on the level of water in storage in University Lake. Stage I is an "alert" that there is a water shortage and requests voluntary water restrictions such as limiting toilet flushes, lawn watering, and car washing. Stage II is a water shortage "warning" that imposes moderate mandatory water restrictions on car washing, pool filling, and lawn watering. Stage III, "danger", imposes severe mandatory water restrictions, and Stage IV, "emergency", imposes even more stringent mandatory restrictions on water usage. The final stage, Stage V or "crisis", makes any failure to comply with the imposed water restrictions unlawful. As shown in Table 2.6, OWASA was not forced to go above Stage II rationing during the period 1985 - 1988.

TABLE 2.6
OWASA's Rationing Dates (1985 - 1988)

Date	Status
July 22, 1985	Stage I imposed
Aug 22, 1985	Stage I rescinded
July 2, 1986	Stage I imposed
July 9, 1986	Stage II imposed
Sept 3, 1986	Stage II rescinded
Oct 16, 1986	Stage II imposed
Dec 8, 1986	Stage II rescinded
Dec 22, 1986	Stage I rescinded
Aug 4, 1987	Stage I imposed
Nov 30, 1987	Stage I rescinded
July 25, 1988	Stage I imposed
Aug 22, 1988	Stage II imposed
Sept 6, 1988	Stage II rescinded
Oct 3, 1988	Stage I rescinded

The average daily demands immediately prior to and during rationing were selected from the historical data trace 1977 - 1988. The data trace were selected back to 1977 to ensure a more reliable estimation of demands. The average demands immediately prior to rationing were calculated by averaging the 30 days of demand prior to rationing. These average daily demand values were plotted and an exponential regression model of the following form was fitted to them (See Figure 2.2 and Tables 2.7 and 2.8).

D_t = alpha exp (beta * t)

where D_t = demand in year t (after some base year 0) and alpha and beta are regression constants.

The historical data trace was examined to determine the effects that different stages of rationing had on demands. When the demands corresponding to each level of rationing were plotted, no distinction could be made between the different stages of rationing that were invoked; that is, the plotted demands for levels of rationing above Stage I were not significantly different than those when Stage I was in effect. Therefore, the demand reduction was calculated for only one type of rationing: either there was rationing or there was not. The regression models used to predict the average daily demand values are:

For unrationed demand: D = 5.01 exp (0.0051 * t)

For rationed demand: D = 3.90 exp (0.0065 * t)

where D = the average daily demand (MGD), and t = the month in which the average daily demand is calculated. Note that the base month, t = 0, is January 1977. The regression statistics for these models are shown in Tables 2.7 and 2.8.

Figure 2.2

Regression Lines To Fit Demand Data With and Without Rationing

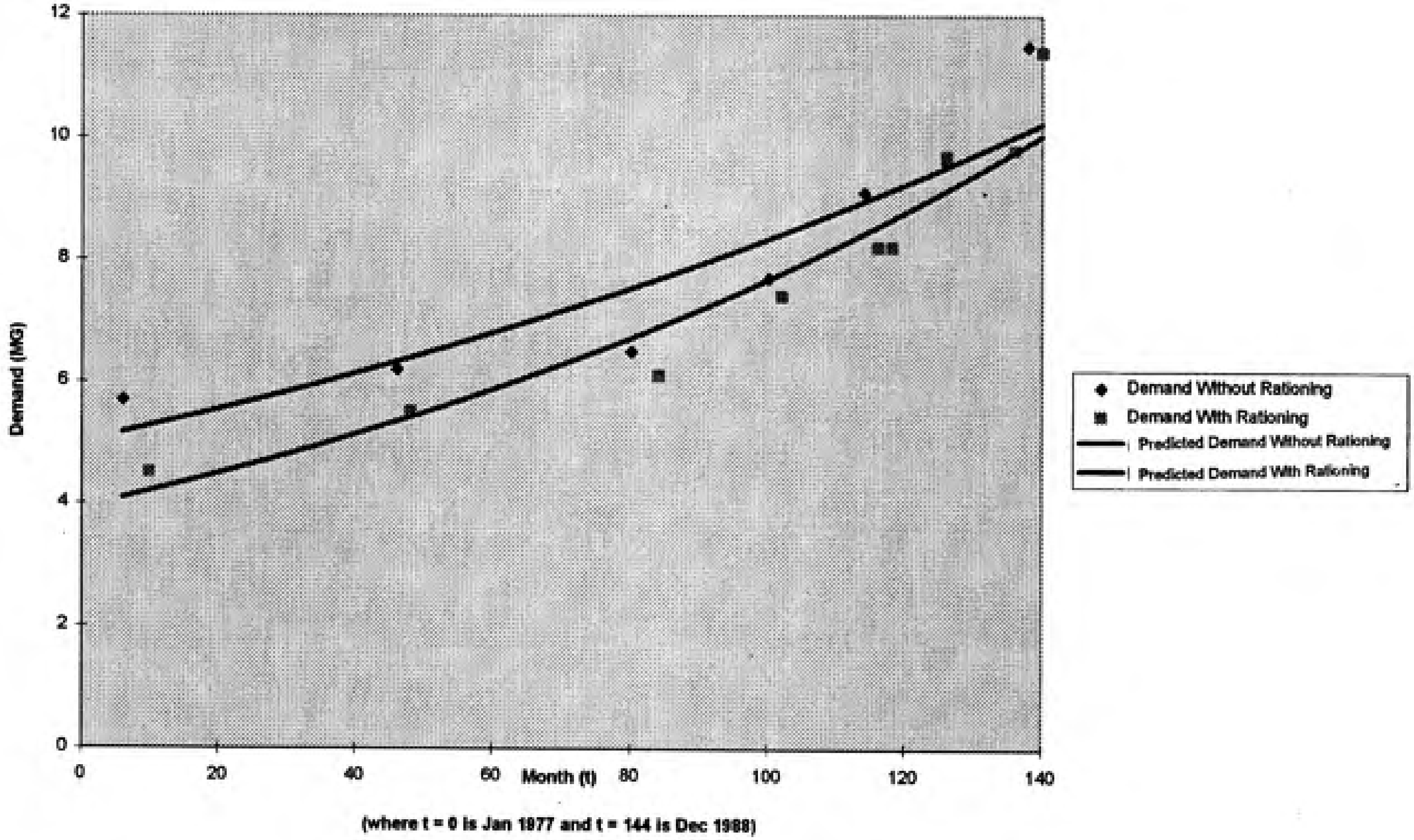


TABLE 2.7
Regression Statistics For Demand Without Rationing Data

t	MGD	ln(MGD)						
6	5.7	1.740466175						
46	6.2	1.824549292						
80	6.5	1.871802177						
100	7.7	2.041220329						
114	9.1	2.208274414						
126	9.6	2.261763098						
138	11.5	2.442347035						
SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0.929310344							
R Square	0.863617716							
Adjusted R Square	0.836341259							
Standard Error	0.10472339							
Observations	7							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	0.347232985	0.347232985	31.66165321	0.002455814			
Residual	5	0.054834942	0.010966988					
Total	6	0.402067928						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.000%*	*Upper 95.000%*
Intercept	1.610693425	0.088450027	18.21020849	9.17907E-06	1.383325765	1.838061085	1.383325765	1.838061085
X Variable 1	0.005107489	0.000907697	5.626868864	0.002455814	0.002774185	0.007440794	0.002774185	0.007440794

Table 2.8
Regression Statistics For Demand With Rationing Data

t	MGD	ln(MGD)							
10	4.5	1.504077397							
48	5.5	1.704748092							
84	6.1	1.808288771							
102	7.4	2.00148							
116	8.2	2.104134154							
118	8.2	2.104134154							
126	9.7	2.272125886							
136	9.8	2.282382386							
140	11.4	2.433613355							
SUMMARY OUTPUT									
Regression Statistics									
Multiple R	0.98283439								
R Square	0.965963438								
Adjusted R Square	0.959156126								
Standard Error	0.054087341								
Observations	7								
ANOVA									
	df	*SS*	*MS*	*F*	*Significance F*				
Regression	1	0.415122504	0.415122504	141.9008552	7.34677E-05				
Residual	5	0.014627202	0.00292544						
Total	6	0.429749706							
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.000%*	*Upper 95.000%*	
Intercept	1.387963801	0.049763463	27.89122203	1.10918E-06	1.260042956	1.515884647	1.260042956	1.515884647	
X Variable 1	0.006435173	0.000507338	11.91221454	7.34677E-05	0.004739366	0.007347669	0.004739366	0.007347669	

The goodness of fit of the models to the data are represented by R-square values of 0.86 for the unrationed demand model and 0.97 for the rationed demand model. The results of the regression analyses are presented in Tables 2.7 and 2.8.

In order to determine the amount of demand reduction, the differences between the average daily demands with and without rationing were calculated. Consider January 1985, for which t = 96. The unrationed demand using the above regression model was 8.2 MGD and the rationed demand from the second model was 7.3 MGD. Hence, in January 1985, rationing had the effect of reducing demand by 0.9 MGD or 27.9 MG per month. Although the demand reduction would be slightly different for the other months in 1985, the January value was used for any month in which rationing occurred during 1985. The other years were handled similarly. The results for all four years of concern in this study are shown in Table 2.9.

TABLE 2.9

DEMAND REDUCTION DUE TO RATIONING

Date	t	Unrationed Demand (MGD)	Rationed Demand (MGD)	Demand Reduction via Rationing (MGD)	Demand Reduction via Rationing (MG/month)
Jan 85	96	8.2	7.3	0.9	27.9
Jan 86	108	8.7	7.9	0.8	24.8
Jan 87	120	9.2	8.5	0.7	21.7
Jan 88	132	9.8	9.2	0.6	18.6

Section 2.6 below presents a simulation of the OWASA system using their rationing policy. In order to develop the simulation for the period 1985 -1989, whenever rationing was invoked, it was assumed to be invoked for the entire month, not just a portion of the month. This means that if rationing were invoked in January 1988, for

example, the demand for that month would decrease by 18.6 MG (0.6 MGD * 31 days). Before the simulation could be made, historical demand data had to be adjusted to reflect unrationed demand. To make the adjustments, the number of days that rationing occurred in the months when rationing was imposed was multiplied by the demand reduction coefficient calculated for that particular year and added to the historical demand. For example, according to the historical data, rationing was imposed for two days during October 1988. To estimate the unrationed demand for that month, the demand coefficient for 1988 from Table 2.9, 0.6 MGD, was multiplied by 2 days and added to the 202.3 MG of historical demand, resulting in 203.5 MG of estimated unrationed demand for October 1988. The estimated unrationed demands for the four years of concern in this report are shown in Table 2.10.

TABLE 2.10
Estimates Of Unrationed Demand
(MG / Month)

	Year			
Month	**1985**	**1986**	**1987**	**1988**
January	145.1	178.2	158.7	185.6
February	134.9	158.8	148.9	179.8
March	157.1	166.0	155.9	189.8
April	180.8	192.1	165.1	193.6
May	169.2	207.4	170.9	203.2
June	163.0	213.4	181.1	209.4
July	155.0	184.4	214.8	193.4
August	179.7	158.8	624.8	146.9
September	200.5	175.8	137.9	144.9
October	198.0	114.1	172.2	203.5
November	179.0	94.8	148.2	197.9
December	160.9	98.5	171.7	193.9

2.5 Working Volume

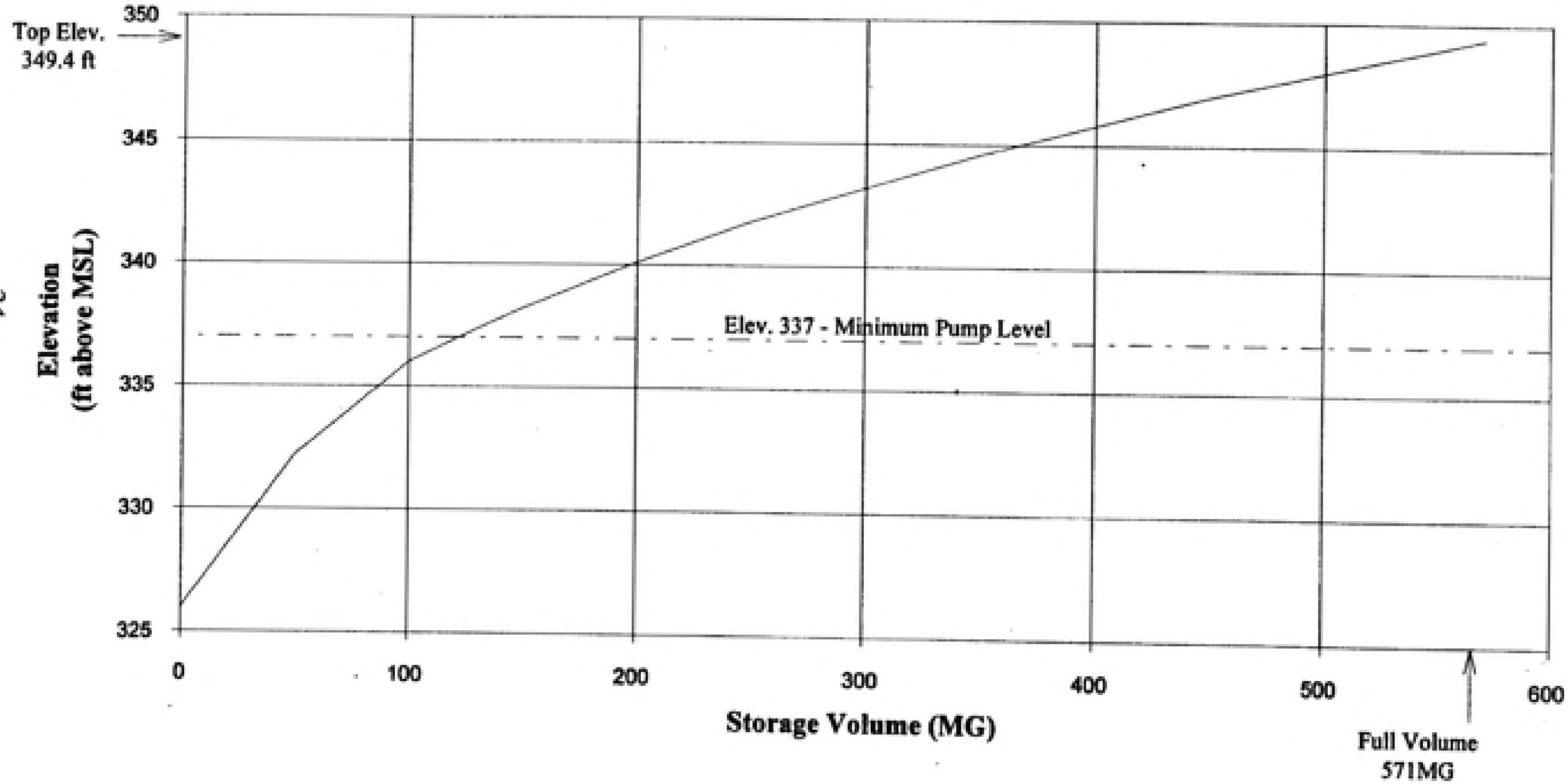
The working volume of a reservoir is the portion of the total storage volume that is usable. For University Lake the limit on drawdown is 12 feet below full, which leaves 120 million gallons (MG) of water in storage; the storage volume of the reservoir when full is 571 MG. Therefore, the maximum working volume for University Lake is 451 MG. This means that the maximum amount of water that is available for use at any given time is 451 MG. The relationship between drawdown and the amount of water in storage is shown in Figure 2.3 and Table 2.11.

TABLE 2.11

University Lake Drawdown-Storage Relationship

Drawdown From Full (Feet)	Amount of Water In Storage (MG)
0	571
1	525.3
2	479.6
3	433.9
4	388.2
5	350
6	316
7	282
8	248
9	214
10	183.3
11	155.5
12	127.7
13	99.9
14	87.5
15	75
16	62.5
17	50
18	41.6
19	33.3
20	25
21	16.7
22	8.4
23	0.1

Figure 2.3
University Lake Drawdown-Storage Curve



2.6 Simulation of OWASA System (1985 - 1988)

Table 2.6 shows the dates when OWASA imposed rationing between 1985 and 1988. The reservoir inflows for this period are in Table 2.1, and the estimated unrationed demands are in Table 2.10. With these data, a simulation can be made to model this historical period. If the simulation requires rationing at the same time that OWASA imposed rationing, then we can be reasonably confident in using the data in the linear programming model of this thesis. However, if the results of the simulation do not match the historical record, then some adjustments will have to be made.

The simulation was made using the inflow data presented in Table 2.1, the (adjusted) unrationed demand data in Table 2.10, and the demand reduction estimates in Table 2.9. The simulation assumed rationing for an entire month whenever it was needed. In order to make the simulation, estimates had to be made of demands whenever rationing is invoked. Hence, the unrationed demand data in Table 2.10 were adjusted to reflect demands that would have to be met if rationing was imposed for an entire month. For example, in January 1985, the estimated unrationed demand from Table 2.10 was 145.1 MG. Table 2.9 shows that if rationing is required for any month in 1985, it would reduce demand by 27.9 MG. Hence, the predicted "rationed demand" for January 1985 is 117.2 MGD (=145.1 - 27.9). Similar values for all of the months are shown in Table 2.13.

The simulation invoked rationing whenever the storage level in University Lake dropped below 480 MG, which is OWASA's rationing policy (See Appendix A). Given that University Lake cannot be drawn down below the level where 120 MG of water remains, this constraint was also added to the simulation. If the storage level drops below the 480 MG trigger level at the end of a month, the simulation invokes rationing for the following month. This triggering of rationing thus tells the simulation to use the values of

Rationed Demand for that month. Otherwise, the values in the Unrationed Demand column are used.

The initial results of the simulation did not exactly match the OWASA historical record of what occurred, although they were close. Therefore, some adjustments were made to the predicted inflows until the simulation results matched the historical record. The adjustments were small as can be seen by comparing the historical inflows to University Lake in Table 2.1 with the "adjusted" inflows in Table 2.12.

Consider the simulation results in Table 2.13. At the beginning of January 1985, the amount of water in University Lake was 523 MG. The inflow in January 1985 was 909.1 (column 4), resulting in total inflow plus storage of 1432.1 MG. However, 145.1 MG was released from the reservoir to meet demand (column 1), resulting in Storage + Inflow - Demand = 1287.0 MG (column 5). Since the reservoir only holds 571 MG, 716.0 MG (1287.0 - 571.0) had to be spilled (column 6), leaving the reservoir full at the end of the month (column 7). Clearly, the combination of inflow plus storage was sufficiently large to avoid rationing (column 8). Simulations for the other months were similiar, except that rationing for the next month was required whenever the amount of water in storage at the end of the previous month fell below the trigger volume of 480 MG. The results of the simulation show the need for rationing during 16 months between January 1985 and December 1988, which are the same months that OWASA invoked rationing during these years. The total reduction in demand due to rationing was 362.2 MG.

TABLE 2.12

Adjusted Monthly Inflows to University Lake (MG/month)

	YEAR			
MONTH	**1985**	**1986**	**1987**	**1988**
January	909.1	275.0	1366.4	770.5
February	1500.1	351.8	1672.1	558.8
March	319.8	827.1	2297.8	341.6
April	151.3	221.4	1275.6	395.0
May	138.2 .	119.8	319.3	187.1
June	55.5	33.2	238.8	64.8
July	104.2	35.5	123.3	23.2
August	251.8	269.8	243.6	26.5
September	200.5	18.1	116.9	90.0
October	198.0	28.1	150.5	545.0
November	2072.0	110.6	507.6	571.5
December	680.6	815.4	444.5	174.0

TABLE 2.13
Simulation Results

1	2	3	4	5	6	7	8
Date	Unrationed Demand (U.Lake)	Rationed Demand (U.Lake)	Monthly Inflows	Storage + Inflow - Demand	Spillage	Storage at end of month	Rationing next month Y=1, N=0
Jan-85	145.1	117.2	909.1	1287.0	716.0	571.0	0
Feb-85	134.9	109.7	1500.1	1936.2	1365.2	571.0	0
Mar-85	157.1	129.2	319.8	733.7	162.7	571.0	0
Apr-85	180.8	153.8	151.3	541.5	0.0	541.5	0
May-85	169.2	141.3	138.2	510.5	0.0	510.5	0
Jun-85	163.0	136.0	55.5	403.0	0.0	**403.0**	1
Jul-85	155.0	127.1	104.2	380.1	0.0	**380.1**	1
Aug-85	179.7	151.8	251.8	480.1	0.0	480.1	0
Sep-85	200.5	173.5	200.5	480.1	0.0	480.1	0
Oct-85	198.0	170.1	198.0	480.1	0.0	480.1	0
Nov-85	179.0	152.0	2072.0	2373.1	1802.1	571.0	0
Dec-85	160.9	133.0	680.6	1090.7	519.7	571.0	0
Jan-86	178.2	153.4	275.0	667.8	96.8	571.0	0
Feb-86	158.8	136.4	351.8	764.0	193.0	571.0	0
Mar-86	166.0	141.2	827.1	1232.1	661.1	571.0	0
Apr-86	192.1	168.1	221.4	600.3	29.3	571.0	0
May-86	207.4	182.6	119.8	483.4	0.0	483.4	0
Jun-86	213.4	189.4	33.2	303.2	0.0	**303.2**	1
Jul-86	184.4	159.6	35.5	179.1	0.0	**179.1**	1
Aug-86	158.8	134.0	269.8	314.9	0.0	**314.9**	1
Sep-86	175.8	151.8	18.1	181.2	0.0	**181.2**	1
Oct-86	114.1	89.3	28.1	120.0	0.0	**120.0**	1
Nov-86	94.8	70.8	110.6	159.8	0.0	**159.8**	1
Dec-86	98.5	70.6	815.4	904.6	333.6	571.0	0
Jan-87	158.7	137.0	1366.4	1778.7	1207.7	571.0	0
Feb-87	148.9	129.3	1672.1	2094.2	1523.2	571.0	0
Mar-87	155.9	134.2	2297.8	2712.9	2141.9	571.0	0
Apr-87	165.1	144.1	1275.6	1681.5	1110.5	571.0	0
May-87	170.9	149.2	319.3	719.4	148.4	571.0	0
Jun-87	181.1	160.1	238.8	628.7	57.7	571.0	0
Jul-87	214.8	193.1	123.3	479.5	0.0	**479.5**	1
Aug-87	624.8	603.1	243.6	120.0	0.0	**120.0**	1
Sep-87	137.9	116.9	116.9	120.0	0.0	**120.0**	1
Oct-87	172.2	150.5	150.5	120.0	0.0	**120.0**	1
Nov-87	168.5	147.5	507.6	480.1	0.0	480.1	0
Dec-87	171.7	150.0	444.5	752.9	181.9	571.0	0
Jan-88	185.6	167.0	770.5	1337.8	766.8	571.0	0
Feb-88	179.8	162.4	558.8	950.0	379.0	571.0	0
Mar-88	189.8	171.2	341.6	722.8	151.8	571.0	0
Apr-88	193.6	175.6	395.0	772.4	201.4	571.0	0
May-88	203.2	184.6	187.1	554.9	0.0	554.9	0
Jun-88	209.4	191.4	64.8	410.3	0.0	**410.3**	1
Jul-88	193.4	174.8	23.2	258.7	0.0	**258.7**	1
Aug-88	146.9	128.3	26.5	156.9	0.0	**156.9**	1
Sep-88	144.9	126.9	90.0	120.0	0.0	**120.0**	1
Oct-88	203.5	184.9	545.0	480.1	0.0	480.1	0
Nov-88	197.9	179.9	571.5	853.7	282.7	571.0	0
Dec-88	193.9	175.3	174.0	833.8	262.8	571.0	0

Chapter 3. LINEAR PROGRAMMING RATIONING MODEL

3.1 Introduction

The purpose of the simulation presented in Section 2.6 was to confirm the inflows and the estimates of demand reduction due to rationing so that they could be used with confidence in the linear programming model of this thesis. The OWASA rationing policy can be tested by using the linear programming model developed herein. The linear programming model is designed to minimize the total amount of required rationing. This test of OWASA's policy compares of the amounts of rationing needed using OWASA's rule versus the amounts of required rationing resulting from the linear programming model.

3.2 The Basic Linear Programming Model

3.2.1 Continuity Constraints

A continuity constraint is a flow balance equation. In this model, the continuity constraint states that the storage in University Lake at the end of any month t must be equal to the storage in the reservoir at the end of the previous month, t - 1, plus any inflows in month t minus any outflows in month t. The continuity constraint in month t for the reservoir can be expressed as:

Amount of Storage in the reservoir at the end of month t	=	Amount of Storage in the reservoir at the end of t - 1	+	Inflows to the reservoir in month t	-	Outflows from the reservoir in month t

A constraint of this type is required for each month for which inflow data to the reservoir are available. Let :

S_t = amount of water in storage at the end of month t

I_t = inflows to the reservoir in month t, a known parameter

O_t = outflows from the reservoir in month t

Hence, $S_t = S_{t-1} + I_t - O_t$ for all t (a)

Note that S_t and O_t are unknown decision variables whose optimal values are to be determined from the model solution. Note further that for O_t we can write:

Outflows from the reservoir in month t	=	Target demand in month t	+	Excess spillage from the reservoir in month t, over and above the target demand	-	Shortfall in meeting the target demand in month t

Let:

D_t = target demand to be met in month t, a known parameter

E_t = excess spillage from the reservoir in month t, over and above the target demand

Q_t = shortfall in meeting the target demand in month t

Hence, we can write:

$O_t = D_t + E_t - Q_t$ for all t (b)

Substituting the right hand side of Eq. (b) for O_t in Eq. (a) we have:

$S_t = S_{t-1} + I_t - D_t - E_t + Q_t$ for all t (c)

Note that E_t and Q_t are unknown decision variables and that if $E_t > 0$ then $Q_t = 0$ and vice versa. In other words, if there is any excess spillage from the reservoir in month t over and above the target demand, then there is no need for any rationing. Following this logic, if $Q_t > 0$, meaning that there is some shortfall in meeting demand in month t, then E_t must equal 0. In Equation (c), all the variables except D_t and I_t are unknown; their optimal values are to be determined by model solution. D_t and I_t, on the other hand, have known numerical values for all t; they were presented in Chapter 2.

3.2.2 Rationing Constraints

Q_t is the shortfall in meeting the target demand in month t, which is the amount of rationing that is needed in month t. The linear programming model asks the computer to determine the optimal amount of rationing for each month t. Note that Q_t has an upper limit based on the maximum amount by which demand can be reduced via rationing. The maximum amounts are shown in the last column of Table 2.9. Hence,

$$Q_t \leq Q_{t(max)} \qquad \text{for all t} \qquad \text{(d)}$$

where $Q_{t(max)}$ is the maximum amount from Table 2.9 by which demand can be reduced via rationing in month t.

Therefore, the model asks the computer to return an optimal value of rationing for each month t, but this value is constrained by the maximum amount of rationing that is possible in that month.

3.2.3 Reservoir Capacity Constraints

The reservoir has a maximum amount of water that it can hold as well as a limit on how far the water level can be drawn down. The maximum amount of water that the reservoir can hold is based on the physical structure of the reservoir. The limit on how far the water level can be drawn down is determined by the piping arrangement for the raw water pumps (the level must be above the crown of the suction pipe) and by water quality issues (taste and odor problems are sometimes encountered when water is drawn from deeper levels). The model must tell the computer what these maximum and minimum volumes of water are so that these capacity constraints are not exceeded. These constraints are expressed as follows:

$S_t \leq S_{max}$ for all t (e)

where S_{max} is the maximum amount of water that the reservoir can hold (571 MG)

and

$S_t \geq S_{min}$ for all t (f)

where S_{min} is the minimum amount of water that must be held in the reservoir (120 MG)

3.2.4 Objective Function

The objective function for the model is simply the total amount of demand reduction due to rationing, which is be to minimized. Alternatively, the purpose of the model is to find the optimal values of rationing each month that minimize the total cost of rationing. Each unit of rationed water has a price assigned to it which is discussed in Section 3.4.5; for now, we can think of the price as being equal to lost revenue. Therefore, the objective function for the basic model can be written as follows:

$$\text{Minimize } \sum_{t} pQ_t \qquad \text{(g)}$$

where p is the price of each unit of rationed water

3.3 Expanded Parametric Model

After the basic model was developed and its results were analyzed, some features were added to refine it and make it more useful; they are described below.

3.3.1 Trigger Volume / Target Storage Constraint

Rationing policies like OWASA's shown in Appendix A are based on the water level in the reservoir. A level is selected, in inches down from the reservoir being full, at which rationing is invoked. This water level can easily be converted into the volume of water remaining in the reservoir. This volume is called the "trigger volume" because when the amount in the reservoir falls below it, rationing is triggered. This volume can also be called the target storage because it is the amount of water that the model attempts to stay above, or "targets". The basic model developed above did not contain this type of constraint, but the expanded model in this section does.

To ensure that the model follows this trigger volume rule, decision variables A_t and B_t must be introduced to the model. A_t is the amount by which the trigger volume is exceeded in month t, and B_t is the shortage in meeting the trigger volume in month t. The decision variables S_t, A_t, and B_t must be constrained as follows:

S_t - the trigger volume = A_t - B_t for all t (h)

Note that if $A_t > 0$ (*i.e.* the amount in storage exceeds the trigger volume) then $B_t = 0$, and vice versa.

3.3.2 Purchasing Option

Water utilities often have the ability to purchase water from an outside source if needed. In this case, OWASA can purchase water from the City of Durham, NC. To make the model more realistic, this option of purchasing outside water was built into the expanded model. There is no limit placed on the amount of water that can be purchased or when the water can be purchased. In order to add this option, the objective function is changed.

3.3.3 Objective Function

The expanded model described above is now called a goal programming model whose objective function is:

$$\text{Minimize} \sum_t pQ_t + \sum_t qB_t + \sum_t p'P_t$$

where: q = the penalty "price" for each unit of water below the trigger volume

p' = the price of each unit of purchased water from an outside source (in this case, from Durham)

P_t = the amount of water purchased in month t from the outside source (a decision variable)

The penalty "price", q, may be non pecuniary (*i.e.* psychological) or pecuniary (*i.e.* higher treatment cost for water of lower quality). This is discussed further in Section 3.4.5.

3.4 Parameter Values

The model has thus far been described in parametric terms, without any numerical values for the parameters. This section discusses such values, which are either determined from historical data or are assigned by judgment.

3.4.1 Inflows

Values for the inflows used in the model were based on historical data, as described in Section 2.2. Tables 2.12, 2.2, and 2.4 present the values used for running the model. Recall that they were of three types: inflows for the period 1985 - 1989; inflows with estimated probabilities of exceedance; and inflows with equal probabilities of occurrence.

3.4.2 Rationing Constraints

The decision variable Q_t, which is the shortfall in meeting the target demand in month t, must be constrained by the maximum amount of rationing allowable in month t. Q_t has an upper limit based upon the maximum amount by which demand can be reduced via rationing. Numerical values for Q_t are shown in the last column of Table 2.9.

3.4.3 Working Volume Constraints

The working volume for University Lake was determined in Section 2.5 to be 571 MG (the volume when full) less 120 MG (dead storage), or 451 MG. When these minimum and maximum storage values are substituted into Eq. (e) and Eq. (f), we can write:

$S_t \leq 571$ MG for all t

and

$S_t \geq 120$ MG for all t

Therefore, at the end of each month the storage volume must be between 120 MG and 571 MG.

3.4.4 Trigger Volume/ Target Storage Constraint

OWASA's rationing policy is based upon a trigger volume of 480 MG (See Appendix A) which is the volume of water remaining in the reservoir when it is only 24 inches below full. Whenever the volume of water in University Lake falls below 480 MG, OWASA would invoke rationing, which may or may not be the case based on the linear programming model of this thesis. Rather, our approach is to treat 480 MG as a target, below which "costs" are incurred. Hence, the value for the "trigger volume" in Eq. (h) is 480 MG.

3.4.5 Prices

The purpose of the model is to determine the optimal amount of water to ration in each month while minimizing costs and meeting constraints. In the basic model of Section 3.2, the only cost in the objective function is the price of each unit of rationed water. This cost basically represents revenue lost by the water authority, but it can also be viewed as a non pecuniary cost, such as the inconvenience to users of having to reduce consumption.

In this case, the price for each unit of rationed water, p, is arbitrarily held constant at $1/MG, which has the effect of converting the objective function into an expression of the total amount of rationed demand. In reality, each MG of rationed demand resulted in a loss of about $2000 to OWASA during the middle 1980s; also there may have been seasonal pricing then which is not considered in the model developed here. The more realistic cost of $2000 per MG of water rationed is explored in a sensitivity analysis at the end of this chapter.

In the expanded model of Section 3.3, prices in addition to the cost of rationing have to be considered. In order to help keep the reservoir storage above the trigger volume level, a penalty "price" is incurred for each unit of water below the trigger volume. This cost is most likely not a pecuniary cost but a psychological cost due to uneasiness in letting the volume of water drop below the trigger level. This penalty would most likely increase as the water level dropped further and further, but in this model it is held constant at $0.01/MG.

Also included in the expanded model is the price of each unit of water purchased from an outside source, p'. To ensure that rationing is chosen before purchasing water from an outside source, the price for each unit of rationing, p, was set at a lower value than the price of purchased water, p'; p' was arbitrarily set at $2/MG which was held constant.

Although it may seem counterintuitive to set up the model to chose rationing before purchasing water given the inconveniences associated with rationing water, this was done in order to have the model behave like OWASA did during 1985 - 1988. If the model was set up to choose purchasing outside water before rationing and if there was no upper limit on the amount of water that could be purchased, then the model would never chose rationing. The purpose of the model is to test OWASA's rationing policy, and in order to do so the prices imposed on the model must be set so that rationing is always chosen over purchasing water from outside.

3.4.6 Initial Conditions

The application of this model was based on a case study. Therefore, the amount of water that was actually in storage at the beginning of 1985 was used for the initial storage value. According to OWASA's historical data, there was 523 MG of water in the reservoir at that time. This initial condition was also placed on the simulation discussed in Section 2.6.

3.5 Baseline Solution of the Basic Model

The model with the parameter values presented above was run using the same data as in the simulation. The optimal amounts of rationing required by the basic linear programming model are shown in Table 3.1 in the columns under the heading "Basic". The results suggest that it was optimal to ration in just 12 months during the four year period; in one month (July 1986) only 0.8 MG is required, which is only one day of rationing. Hence, for all intents and purposes, it was optimal to ration in only 11 months from 1985 through 1988.

3.5.1 Comparison With OWASA's History

3.5.1.1 When To Ration

Table 3.1 compares the amounts of rationing required by the basic linear programming model run with the OWASA historical data. The results of the baseline run indicate a lesser need for rationing than what was actually undertaken by OWASA. During the four years of this study, OWASA rationed for a total of 16 months. The results of the linear programming model indicate that no rationing was necessary in 1985, but OWASA rationed during two months (July and August) that year. In 1986, the linear programming model denoted the need for rationing in four of the twelve months (June, August, September, and October) whereas OWASA implemented rationing for six months during that year.* The linear programming model also indicated that rationing should have begun in June 1986 rather than July, which was when OWASA started to ration. In 1987, OWASA implemented rationing during four months of the year while the model recommends rationing for only three months (August, September, and October). Finally, the model suggests rationing during four months (May, June, August, and September) in 1988 compared to OWASA, which rationed during July, August, September, and October.

In 1986 and 1988, the basic model invokes rationing, stops it for a month, and then invokes it again, which could be confusing to customers and may not be realistic. The model could be modified by adding a constraint that would not allow this to happen. Overall, the basic linear programming model suggests starting rationing earlier than OWASA did in 1986 and 1988.

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*The linear programming model suggests rationing only 0.8 MG in July 1986 ($t = 19$) which is equivalent to only one day of rationing.

TABLE 3.1

Comparisons of Amounts of Required Rationing (MG)

	1985			1986			1987			1988		
	OWASA[1]	Basic[2]	Exp[3]	OWASA	Basic	Exp	OWASA	Basic	Exp	OWASA	Basic	Exp
Jan	0	0	0	0	0	0	0	0	0	0	0	0
Feb	0	0	0	0	0	0	0	0	0	0	0	0
Mar	0	0	0	0	0	0	0	0	0	0	0	0
Apr	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	24.8	0	0	0	0	16.1	16.1
Jun	0	0	0	0	24.0	24.0	0	0	0	0	18.0	18.0
Jul	27.9	0	0	24.8	0.8	24.8	0	0	21.7	18.6	0	18.6
Aug	27.9	0	0	24.8	24.8	24.8	21.7	21.7	21.7	18.6	3.1	2.5
Sep	0	0	0	24.0	24.0	0	21.0	21.0	21.0	18.0	18.0	0
Oct	0	0	0	24.8	24.8	0	21.7	21.7	0	18.6	0	0
Nov	0	0	0	24.0	0	0	21.0	0	0	0	0	0
Dec	0	0	0	24.8	0	0	0	0	0	0	0	0
Total	55.8	0	0	147.2	98.4	98.4	85.4	64.4	64.4	73.8	55.2	55.2

(1) According to the OWASA historical data
(2) According to the basic linear programming model
(3) According to the expanded linear programming model

3.5.1.2 How Much To Ration

The baseline results indicate a lesser amount of rationing during the four years than OWASA required. The values of required rationing are shown in Table 3.1. For example, the OWASA simulation suggested rationing a total of 55.8 MG of water during 1985, but the model indicated no rationing was needed during this period. There is an overall four-year total difference of 144.2 MG of rationing between OWASA's history (362.2 MG) and the model results (218 MG).

3.5.1.3 Storage Volumes

The amount of water in storage in the reservoir at the end of each month in the baseline results is quite low most of the time, as can be seen in Table 3.2. The storage volumes tend to hover around the minimum amount that is required to be in the reservoir at any given time. This is because there is no constraint to keep the reservoir full or near full in the basic linear programming model.

More interesting than the end-of-month storage volumes are the amounts of water in storage before rationing is invoked. The storage volume at the end of May 1986, t = 17, was 483.4 MG. In t = 31, July 1987, the storage volume at the end of the month was 479.5 MG, which is about the same as OWASA's trigger volume level. However, at the end of April 1988, t = 40, the amount of water in storage was 571 MG, which means the reservoir was full. These storage volume results and the linear programming model's tendency to start rationing earlier may suggest that the use of a trigger volume alone as the criterion for rationing is inadequate.

TABLE 3.2

Comparisons of Amounts of Water in Storage at the End of Each Month (MG)

	1985			1986			1987			1988		
	OWASA[1]	Basic[2]	Exp[3]	OWASA	Basic	Exp	OWASA	Basic	Exp	OWASA	Basic	Exp
Jan	571	120	480	571	120	480	571	120	480	571	120	480
Feb	571	176.1	480	571	120	480	571	120	480	571	217.9	480
Mar	571	338.3	571	571	541.7	541.7	571	120	480	571	369.6	480
Apr	541.5	309.3	541.5	571	571	571	571	364.9	480	571	571	571
May	510.5	278.3	510.5	483.4	483.4	508.2	571	513.3	513.3	554.9	571	571
Jun	403	170.8	403	303.2	327.2	352	571	571	571	410.3	444.4	444.4
Jul	380.1	120	352.2	179.1	179.1	227.9	479.5	479.5	501.2	258.7	274.2	292.8
Aug	480.1	120	424.3	314.9	314.9	363.7	120	120	141.7	156.9	156.9	174.9
Sep	480.1	120	424.3	181.2	181.2	206	120	120	141.7	120	120	120
Oct	480.1	120	424.3	120	120	120	120	120	120	480.1	120	461.5
Nov	571	120	480	159.8	120	135.8	480.1	120	459.1	571	139.9	499.9
Dec	571	120	480	571	120	480	571	120	480	571	120	480

(1) According to the OWASA historical data
(2) According to the basic linear programming model
(3) According to the expanded linear programming model

3.6 Expanded Model (Goal Programming) Solution

The model, in its expanded form, with a penalty imposed for falling below the target volume and with the option of purchasing water from an outside source, was run next. The values discussed in Section 3.4 were used in this model run. These values include a price of $1/MG of rationed water, a penalty of $0.01/MG of water below the target volume, and a price of $2/MG for purchased water. The amounts of rationing required by the expanded linear programming model are shown in Table 3.1 in the columns under the heading "Exp".

3.6.1 Comparisons With OWASA's History And The Basic Linear Programming Model

3.6.1.1 When To Ration

Table 3.1 compares the timing and amounts of rationing required by the expanded linear programming model with OWASA's historical data. The results from the expanded model indicate a lesser need for rationing than what was actually undertaken by OWASA. During the four years, OWASA rationed for a total of 16 months, whereas the expanded model only called for rationing in 11 months, one of which only needed rationing for about four days. No rationing was required in 1985 according to the expanded model, but OWASA rationed for two months (July and August) that year. In 1986, the expanded model suggested rationing for four of the twelve months (May, June, July, and August) whereas OWASA rationed six months that year. The expanded linear programming model also indicated that rationing should begin in May 1986 rather than July, which was when OWASA started to ration. In 1987 OWASA rationed during four months of the year while the model recommends rationing only three months (July, August, and September). Again the expanded model suggests that rationing should have begun a month earlier than it did based on historical records. Finally, the model suggests rationing during four months

(May, June, July, and August) in 1988 compared to OWASA, which rationed during July, August, September, and October. The expanded linear programming model suggests starting rationing earlier than OWASA in each of the years that rationing occurred and earlier than the basic model did in 1986 and 1987. This tendency for the expanded linear programming model to begin rationing earlier was driven by the penalty for dropping below the target volume of 480 MG.

3.6.1.2 How Much To Ration

The expanded model results show that less rationing was needed during the four years than OWASA required. For example, the OWASA simulation suggested rationing a total of 55.8 MG of water during 1985, but the expanded model indicated that no rationing was required. There is an overall four year total difference of 144.2 MG between the OWASA historical data and the expanded model results.

Although the basic model and the expanded model results require rationing at slightly different times, the total amount of rationing is the same. Both models suggest no rationing in 1985, 98.4 MG in 1986, 64.4 MG in 1987, and 55.2 MG in 1988. The expanded model rations in a more sensible manner during 1986 than the basic model by incorporating the 0.8 MG of rationing in July 1986 into the previous month and by not skipping a month of rationing in 1988.

3.6.1.3 Storage Volumes

The amount of water in storage at the end of each month calculated by the expanded model results is only slightly lower than the storage amounts at the end of each month in the OWASA simulation, as can be seen in Table 3.2. The storage volumes in the expanded model tend to hover around 480 MG for falling below which a penalty is incurred. The amount of storage in the reservoir at the end of each month is greater in the expanded model results than in the basic linear programming model results because ofthe penalty. Clearly, a different target storage would have resulted in different optimal storgae volumes.

More interesting than the end-of-month storage volumes are the amounts of water in storage before rationing is invoked. The storage volume at the end of each month immediately before rationing is invoked (April 1986, June 1987, and April 1988) is 571 MG, meaning the reservoir is full. A lower target would probably not require rationing when the resevoir is full.

3.6.1.4 Purchased Water

The option of purchasing water from an outside source is included in the expanded model. In the expanded model case, the prices are set at $1/MG of rationed water (p) and $2/MG (p') of purchased water. Therefore, to minimize the objective function in this case, the option to purchase water from an outside source is not used. If however, the cost of rationing water were higher than the price of purchasing water, then the purchasing option would probably be used. This conclusion is explored in the sensitivity analyses section at the end of this chapter.

3.6.1.5 Objective Function Value

The objective function value from the expanded linear programming model run is $256 while the value of the basic linear programming model run is $218. This difference in objective function values is due to the penalty imposed on each unit of water when the target storage volume level is not met.

3.7 Sensitivity Analyses

An important value of a model like the one in this report is for performing sensitivity analyses. A sensitivity analysis involves making changes in the inputs of the model and observing the differences in the outputs. To perform a sensitivity analysis, a baseline case must be established for making comparisons. The baseline solution for the expanded linear programming model described in Section 3.6 is the one to which most of the sensitivity analyses are compared in this report. A sensitivity analysis shows which inputs affect the results by the greatest amounts. If the model is particularly sensitive to certain inputs, this could suggest that any applications that rely heavily on those inputs may be unreliable. Sensitivity analyses were performed for the price of rationed water (p) and the penalty for falling below the trigger level (q).

3.7.1 Price of Rationed Water

If the price of rationing was greater than the price of purchasing water from Durham, then the model would always choose to purchase. As long as the price of rationing is less than the price of purchasing, the model will choose to ration. When the price of rationing equals the price of purchasing, then the results show a mix of the two options, with the majority being to purchase in order to keep the working volume close to the target and thereby minimize the penalties for falling it.

3.7.2 Lost Revenue

One of the runs in this analysis set the price of rationed water at $2000 / MG, which is fairly realistic price for this case. The results indicated a predicted lost revenue of

$436,000 for the 218 MG of water that needed to be rationed; the optimal amount of rationing was the same for prices of $1/MG and $2000/MG. The predicted loss of $436,000 may actually underestimate lost revenue.

This information is important to OWASA because it gives them an incentive to reduce the amount of rationing. The community does not like any amount of rationing because of the inconvenience it imposes. However, avoiding this inconvenience is not always an option. Similarly, OWASA dislikes the prospect of losing revenue due to rationing.

CHAPTER 4. RATIONING POLICY

4.1 Introduction

The model in Chapter 3 was only used for *ex post facto* analyses; it had the benefit of hindsight. If we want to use the linear programming model for making *ex ante* decisions about rationing (*i.e.* when future inflows are unknown), how can we do it ? This chapter presents two ways: a chance constrained approach and an expected value approach.

4.2 Chance Constrained Approach

The first way that the model can be used as an *ex ante* decision making tool is the chance constrained approach. In this approach, the chance constraints incorporate the stochastic nature of inflows into the deterministic formulation of the model. Recall from Section 2.2 that we can predict any monthly inflows with a given probability of exceedance, p. We can then use the predicted inflows in the linear programming model to obtain results that have a given level of chance assigned to them. For example, if the monthly inflows in Table 2.2 that correspond to a probability of exceedance of 95 percent are used to run the model, then all of the continuity constraints that involve these inflows would be satisfied with 95% reliability (Loucks, *et al.*, 1981; Revelle, *et al.*, 1969). The levels of reliability of the constraints in the model can be set at any desired probability of exceedance. This technique has been applied with success in several cases (Eisel, 1972; Joeres, *et al.* , 1971; Nayak and Arora, 1971; Revelle and Kirby, 1970).

Using this chance constrained approach, the model was run using inflows in Table 2.2 that correspond to probabilities of exceedance of 0.5, 0.90, 0.95, and 0.99. Each set of inflows was randomly assigned to one of the years of demand data (1985 - 1988). The expanded linear programming model was run using these newly assigned inflow data, a price of $1/MG of rationed water, a penalty of $0.01/MG for falling below the target volume, and a price of $2/MG of purchased water. The amounts of required rationing that resulted from this run can be seen in Table 4.1.

The results of the linear programming model using this chance constrained approach suggest rationing in 24 months during the four year period, 1985 - 1988. Using inflows with a probability of exceedance of 50% and 1985 demands, the model proposes rationing a total of 111.5 MG of water. The model does not suggest purchasing any water from Durham, NC. When the predicted inflows with a probability of exceedance of 99% were assigned to 1986 demands, the model suggests rationing a total of 145.9 MG of water and purchasing a total of 0.9 MG of water. The 1987 demand data and the predicted inflows with a given probability of 95% were matched together resulting in the model suggesting rationing a total of 128.1 MG of water. The model also suggests purchasing 82.3 MG of water from Durham, NC in July and 474.4 MG of water in August. Using 1988 demands with predicted inflows with a probability of exceedance of 90%, the model suggests rationing a total of 122.5 MG and purchasing a total of 148 MG of water from Durham, NC.

This approach can be very helpful when attempting to determine the amount of rationing that will be required in the future. Optimal amounts of required rationing can be predicted with a certain level of reliability by using predicted inflows with a given probability of exceedance. If a very conservative estimate is desired, the inflows corresponding to a very high level of probability (i.e. 99%) should be used.

TABLE 4.1

Amounts of Required Rationing Using The Chance Constrained Approach (MG)

	1985(1)	1986(2)	1987(3)	1988(4)
Jan	0	0	0	0
Feb	0	0	0	0
Mar	0	0	0	0
Apr	0	0	0	0
May	0	23.5	0	12.7
Jun	13	24	21	18
Jul	27.9	24.8	21.7	18.6
Aug	27.9	24.8	21.7	18.6
Sep	27	24	21	18
Oct	15.7	24.8	21.7	18.6
Nov	0	0	0	18
Dec	0	0	0	0
Total	111.5	145.9	128.1	122.5

(1) Exceedance probability for inflows in 1985 was 50%
(2) Exceedance probability for inflows in 1986 was 99%
(3) Exceedance probability for inflows in 1987 was 95%
(4) Exceedance probability for inflows in 1988 was 90%

4.3 Expected Value Approach

The second approach that was investigated is referred to as the expected-value approach, which determines the expected amount of rationing in each month. This approach entails running the expanded linear programming model with a range of inflows having equal probabilities of occurrence, which are listed in Table 2.3. The ten years of inflows shown in bold type are the ones that were used for this analysis. Each year was assigned a number from one to ten, and a random number generator was used to select which one of the four sets of demand data (1985 - 1988) would be used with each of the ten sets of inflows data for each run. By running the model ten times, each with an inflow with a probability of occurrence of 10%, the expected amount of rationing for each month can be obtained by simply adding the total amount of rationing for all ten runs and dividing by ten.

The results of each run can be seen in Table 4.2. The results for years considered to be wetter suggest very little or no rationing while the results for the drier years suggest significant amounts of rationing. For example, when the 1982 and 1979 inflows were used, the model does not require any rationing nor any purchasing of water from Durham, NC. Both of these years are considered to be "wet" years. However, when the 1977 inflows were used, the model required purchasing a total of 177.6 MG of water from Durham, NC and rationing in May, June, July, August, September, and October, for a total of 147.2 MG. 1977 is the "driest" year of the ten years used in the runs.

The expected amount of rationing in each month can be seen in Table 4.3. These values were obtained by adding the amounts of rationing required in each month using the ten different traces of inflow data. These totals were then multiplied by 0.1, the probability of occurrence of each inflow trace, to estimate the amount of required rationing that can be expected in each month.

TABLE 4.2

Amounts of Required Rationing Using The Expected Value Approach (MG)

	1966(1)	1979(2)	1975(3)	1983(4)	1963(1)	1977(2)	1982(3)	1970(4)	1973(1)	1967(2)
Jan	0	0	0	0	0	0	0	0	0	0
Feb	0	0	0	0	0	0	0	0	0	0
Mar	0	0	0	0	0	0	0	0	0	0
Apr	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	24.8	0	0	0	0
Jun	27.9	0	0	0	27	24	0	0	0	0
Jul	27.9	0	0	18.6	27.9	24.8	0	0	0	0
Aug	27	0	21.7	18.6	27	24.8	0	0	0	0
Sep	27.9	0	0	18	20.6	24	0	0	15.4	0
Oct	27	0	0	18.6	0	24.8	0	0	0	0
Nov	0	0	0	0	0	0	0	0	0	0
Dec	0	0	0	0	0	0	0	0	0	0
Total	137.9	0	21.7	73.8	102.5	147.2	0	0	15.4	0

(1) 1985 demands were used
(2) 1986 demands were used
(3) 1987 demands were used
(4) 1988 demands were used

TABLE 4.3

Expected Amount of Rationing Arranged from Wettest to Driest Years (MG)

					Year						
Mo.	1982[3]	1979[2]	1975[1]	1973[1]	1970[4]	1967[2]	1983[4]	1963[1]	1966[1]	1977[2]	Total	EV
Jan	0	0	0	0	0	0	0	0	0	0	0	0
Feb	0	0	0	0	0	0	0	0	0	0	0	0
Mar	0	0	0	0	0	0	0	0	0	0	0	0
Apr	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	24.8	24.8	2.5
Jun	0	0	0	0	0	0	0	27	27.9	24	78.9	7.9
Jul	0	0	0	0	0	0	18.6	27.9	27.9	24.8	99.2	9.9
Aug	0	0	21.7	0	0	0	18.6	27	27	24.8	119.1	11.9
Sep	0	0	0	15.4	0	0	18	20.6	27.9	24	105.9	10.6
Oct	0	0	0	0	0	0	18.6	0	27	24.8	70.4	7.0
Nov	0	0	0	0	0	0	0	0	0	0	0	0
Dec	0	0	0	0	0	0	0	0	0	0	0	0

(1) 1985 demands were used
(2) 1986 demands were used
(3) 1987 demands were used
(4) 1988 demands were used

CHAPTER 5. DISCUSSION AND CONCLUSIONS

5.1 *Ex Post Facto* Versus *Ex Ante* Applications Of Model

The *ex post facto* use of this model provided a way to test the OWASA rationing policy. Chapter 4 discussed a couple of approaches for using this model as an *ex ante* decision tool. The model can provide expected values of uncertain variables as seen in the expected value approach discussed in Section 4.3, where the expected value of rationing in each month was calculated by using a set of ten inflows ranging from "wet" to "dry", each with an equal probability of ocurrence ($p = 0.1$).

The water authority can also estimate the required amount of rationing by using the chance constrained approach. In this particular case, this approach uses inflows that have a given probability of exceedance. For example, inflows exceeded 95% of the time can be used to determine a conservative estimate of the amount of rationing that will be required.

A third way that this model can be used as an *ex ante* decision making tool is called the simulation approach. This approach was not applied in this report, but it may be a useful tool for future work. Suppose the reservoir operator finds herself in July with X MG of water in storage and projected demands to be met in August of D8, in September of D9, in October of D10, etc. Using the linear programming model, X can be inserted for the amount of storage at the end of June, the projected D values can be used for the demand constraints, and the operator can solve several "what if" scenarios. For example, what if the inflows for the next 12 months are those that are exceeded 90% of the time? Then solve for 95%, etc. Now look only at the results for August to get an idea of what to do next month.

5.2 The OWASA Rationing Policy

According to an analysis of the model results presented in this report, it appears that OWASA rationed somewhat more than was theoretically necessary during the four year period, 1985 - 1988. The decisions regarding when and how much water to ration during these years were made without consideration of limited rationing. OWASA made solid and effective decisions with the information that it had.

Although OWASA seemed to do pretty well using their rationing policy, it seems that the policy may be too simplistic. The linear programming model in this report, with the advantage of hindsight, shows that the required amount of rationing could have been reduced. The model results consistently suggest starting rationing earlier than OWASA's policy. These results suggest that a policy based solely on a trigger volume level may be inadequate; it is probably insufficient to minimize the amount of required rationing by using a policy that is based only on the amount of water in storage. It may be useful to develop a rationing policy that incorporates other variables in addition to the amount of water in storage in the reservoir as criteria on which to make decisions regarding rationing. A linear programming model such as the one developed in this report could provide a means for constructing a more effective rationing policy.

5.3 Model Modification

Numerous modifications of the model are possible. For example, several target volumes with different penalties could be assumed. Also, a penalty could be imposed to minimize excess spillage and/or a benefit could be granted for keeping the reservoir as full as possible. These modifications would undoubtedly affect the optimal amounts and patterns of rationing. By working sensitivity analyses, it should be possible to identify the key determinants of an optimal rationing policy.

REFERENCES

Eisel, L.M., "Chance Constrained Reservoir Model", *Water Resources Research*, Vol. 8, No. 2, pp. 339 - 342, April 1972.

Gutmann, Jennifer L., "Optimal Operation and Long Range Planning of the OWASA Water Supply System", masters technical report, UNC - CH Department of Operations Research, 1995.

Joeres, Erhard F., Jon C. Liebman and Charles S. Revelle, "Operating Rules for Joint Operation of Raw Water Sources", *Water Resources Research*, Vol. 7, No. 2, pp. 225 - 235, April 1971.

Loucks, Daniel P., Jery R. Stedinger and Douglas A. Haith, Water Resources Systems Planning and Analysis, Prentice - Hall, Inc., Englewood Cliffs, NJ, 1981.

Nayak, Satish C. and Sant R. Arora, "Optimal Capacities for a Multireservoir System Using the Linear Decision Rule", *Water Resources Research*, Vol. 7, No. 3, pp. 485 - 498, June 1971.

Revelle, Charles, Erhard Joeres and William Kirby, "The Linear Decision Rule in Reservoir Management and Design. 1. Development of the Stochastic Model", *Water Resources Research*, Vol. 5, No. 4, pp. 767 - 777, August 1969.

Revelle, Charles S. and William Kirby, "The Linear Decision Rule in Reservoir Management and Design. 2. Performance Optimization", *Water Resources Research*, Vol. 6, No. 4, pp. 1033 - 1044, August 1970.

Speight, Vanessa, "Optimization of the Operation of a Multiple Reservoir System Using 0,1 Mixed Integer Programming", masters technical report, UNC - CH Department of Environmental Sciences and Engineering, 1994.

XA Professional Linear Programming System, Sunset Software, 1613 Chelsea Road, Suite 153, San Marino, CA 91108, 1987.

APPENDIX A

OWASA'S RATIONING POLICY

AN ORDINANCE PROVIDING FOR CONSERVATION OF WATER DURING A WATER SHORTAGE, AND FOR RESTRICTIONS ON THE USE OF WATER DURING MORE SEVERE SHORTAGES (84-O-70)

WHEREAS, University Lake provides the primary source of raw water from which the Orange Water and Sewer Authority supplies water to the Town of Chapel Hill, and

WHEREAS, the level of said lake indicates the amount of reserve water available and the need to conserve water, or restrict its use, and

WHEREAS, it is essential for the protection of the health and safety of the citizens of Chapel Hill that restrictive measures be imposed upon the use of water supplied within the Town of Chapel Hill and the surrounding territory through the facilities of the Orange Water and Sewer Authority, in the event the reserve supply reaches from below normal to critical levels.

NOW, THEREFORE, BE IT ORDAINED by the Town Council of the Town of Chapel Hill:

SECTION I.

That the Council hereby amends Chapter 11 of the Code of Ordinances by adding a new Article X as follows:

Section 11-101. Water Shortage Deemed in Light of Reserve Water Supply

A water shortage shall be deemed to exist when the reserve supply available through the facilities of the Orange Water and Sewer Authority shall have reached the point where the reserve supply has been so reduced that the citizens cannot be supplied with water to protect their health and safety without curtailing substantially the water demand.

Section 11-102. Proclamation of Water Shortage

In the event of a water shortage in any of the five degrees of severity hereinafter set forth in the Town Water Supply threatening the health and safety of the citizens of the Town, the Mayor of the Town of Chapel Hill is authorized, empowered, and directed to issue a public proclamation declaring to all persons the existence of such state and the severity thereof, and in order to more effectively protect the health and safety of the people within the Town of Chapel Hill, to place in effect the restrictive provisions hereinafter authorized.

Section 11-103. Compliance Required in the Event of Shortage

In the event the Mayor issues any such proclamation described in Section II, then and in that event it shall be unlawful for any person, firm, or corporation, to use or permit the use of water from the water system within the Town of Chapel Hill supplied through the facilities of the Orange Water and Sewer Authority for any of the purposes hereinafter set forth until such time as this Ordinance be amended or repealed, or until the Mayor, by public proclamation, has declared certain provisions no longer in effect. In exercising this discretionary authority, consideration shall be given to: water levels of available sources of supply; available/usable shortage on hand; drawdown rates; the projected supply capability; outlook for precipitation; daily water use patterns; and availability of water from other sources.

In light of the many benefits that can be derived by conserving water, all residents, businesses and institutions in the community should follow water conservation practices, regardless of the time of year or whether or not a water shortage exists. Water conservation should be followed during all phases of construction related activities. Where appropriate, water needed should be obtained from supplemental sources and non-essential construction-related activities which require water should be delayed until such time as the water emergency has ended.

Section 11-104. Restrictions Applicable Various Water Levels at University Lake

The severity of the water shortage shall be determined by the level of University Lake, and the restrictive measures in effect at each stage are as follows:

A. In the event the water level of University Lake declines to a level of 347 feet above mean sea level (24 inches below full) a stage I of water shortage ALERT shall be deemed in effect, and the following voluntary water restrictions imposed: may be declared

1. An extensive publicity campaign will be initiated using public media and specialized methods to inform the public of an impending water shortage.

2. Residential conservation measures will be encouraged and recommended including the following:

   a. Use shower for bathing rather than bathtub and limit shower to no more than four (4) minutes.

   b. Limit flushing of toilets by multiple usage.

   c. Do not leave faucets running while shaving or rinsing dishes.

   d. Limit use of clothes washers and dishwashers and when used, operate fully loaded.

   e. Limit lawn watering to that which is necessary for plants to survive.

   f. Water shrubbery the minimum required, reusing household water when possible.

   g. Limit car washing to the minimum.

   h. Do not wash down outside areas such as sidewalks, patios, etc.

i. Install water flow restrictive devices in shower heads.

j. Use disposable and biodegradable dishes.

k. Install water saving devices such as bricks, plastic bottles or commercial units in toilet tanks.

l. Limit hours of operation of water-cooled air conditioners.

3. It is recommended that water supply line pressure reducing valves be set to the minimum necessary for effective operations of fixtures and equipment.

4. Conservation in public buildings, institutions, dormitories, etc. is encouraged by reducing pressure at plumbing fixtures, by installation of restricting devices and shutting down on water flow control devices, and by only periodic flushing of urinals.

5. All residents, businesses and institutions are requested to temporarily delay new landscape work until the work shortage has ended.

6. Local governing bodies will utilize untreated or reclaimed water for street washing, landscape irrigation, and other appropriate purposes to the extent practical and will implement in their facilities the water conservation measures required under a stage II WARNING of the ordinance.

B. In the event the water level of University Lake declines to the level of 346 feet above mean sea level (36 inches below full), a stage II water shortage WARNING shall be deemed in effect, and in addition to the restrictions heretofore imposed, the following moderate mandatory water restrictions shall be in effect. It shall be unlawful to use water from the public water system supplied by Orange Water and Sewer Authority for the following purposes:

1. To water lawns, grass, shrubbery, trees, flower and vegetable gardens except as follows:

Customers located to the south of the centerline of NC 54 West, Main Street in Carrboro, Franklin Street, and US 15/501 Boulevard may water lawns, grass, shrubbery, trees, flower and vegetable gardens on Saturday morning between the hours of 6:00 am and 9:00 am.

Customers located to the north of the centerline of NC 54 West, Main Street in Carrboro, Franklin Street, and US 15/501 Boulevard may water lawns, grass, shrubbery, trees, flower and vegetable gardens on Sunday morning between the hours of 6:00 am and 9:00 am.

Such watering is to be done by hand-held hose or container or drip irrigation system.

2. To fill newly constructed swimming and/or wading pools or refill swimming and/or wading pools which have been drained. A minimal amount of water may be added to maintain continued operation of pools which are in operation at the time the provisions of a stage II WARNING are placed into effect.

3. To operate water-cooled air conditioners or other equipment that does not recycle cooling water, except when health and safety are adversely affected.

4. To wash automobiles, trucks, trailers, boats, airplanes, or any other type of mobile equipment, including commercial washing.

5. To wash down outside areas such as streets, driveways, service station aprons, parking lots, office buildings, exteriors or existing or newly constructed homes or apartments, sidewalks, or patios, or to use water for other similar purposes.

6. To operate or introduce water into any ornamental fountain pool or pond or other structure making similar use of water.

7. To serve drinking water in restaurants, cafeterias, or other food establishment, except upon request.

8. To use water from public or private fire hydrants for any purpose other than fire suppression or other public emergency.

9. To use water for dust control or compaction.

10. To use water for any unnecessary purpose or to intentially waste water.

The owner or occupant of any land or building which receives water from Orange Water and Sewer Authority and that also utilizes water from a well or supply other than that of Orange Water and Sewer Authority shall post and maintain in a prominent place thereon a sign furnished by Orange Water and Sewer Authority giving public notice to the use of the well or other source of supply.

may be declared

C. In the event the lake level of University Lake declines to the level of 344.5 feet above mean sea level (54 inches below full), a stage III water shortage DANGER shall be deemed to exist, and in addition to the restrictions heretofore imposed, the following severe mandatory water restrictions shall be in effect. It shall be unlawful:

1. To water or sprinkle any lawn.

2. To water any vegetable garden or ornamental shrubs except during the hours of 6:00 a.m. to 9:00 a.m. on Saturday. Such watering is only to be done by hand-held hose or container or drip irrigation system.

3. To make any non-essential use of water for commercial or public use, and the use of single service plates and utensils is encouraged and recommended in restaurants.

D. In the event the level of University Lake declines to the level of 343 feet above mean sea level (72 inches below full), a stage IV water shortage emergency shall be deemed to exist and in addition to the restrictions heretofore imposed, the following stringent mandatory water restrictions shall be in effect. It shall be unlawful:

1. To use water outside a structure for any use other than an emergency use involving fire.

2. To operate an evaporative air conditioning unit which recycles water except during the operating hours of the business.

3. To introduce water into any swimming pool.

E. In the event the level of University Lake declines to the level of 341 feet above mean sea level (96 inches below full), a stage V water shortage CRISIS shall be deemed in effect, and a system of water rationing shall be put in effect in addition to all previously imposed restrictions. In the event of water rationing in which water will be supplied in the minimal quantities required for the health, welfare, and safety of the citizens in accordance with a program determined by the Orange Water and Sewer Authority:

1. It shall be unlawful to fail to act in accordance therewith or use water in any manner or attempt to evade or avoid such water rationing restrictions.

2. Fire protection will be maintained, but where possible tank trucks shall use raw water.

Section 11-105. Penalties.

Any violations of the provisions of the Ordinance shall constitute a misdeameanor punishable upon conviction by a fine not exceeding FIFTY DOLLARS ($50.00) or imprisonment not exceeding thirty (30) days as provided by General Statute Section 14-4 and in addition thereto such violation may be enjoined and restrained as provided in General Statute Section 160A-175.

Section 11-106. Injunctive Remedies.

Pursuant to the provisions of General Statute Section 160A-193, the injunctive remedies therein provided shall be applicable for the summary abatement or remedying of appropriate conditions dangerous or prejudicial to the public health both within the town limits of the Town of Chapel Hill and within one mile thereof and the expense thereof assessed as therein provided.

Section 11-107. Severability.

If any section, subdivision, clause, or provision of the Ordinance shall be adjudged invalid, such adjudication shall apply only to such section, subdivision, clause, or provision so adjudged, and the remainder of this Ordinance shall be deemed valid and effective.

SECTION II

All Ordinances and clauses of Ordinances in conflict herewith are hereby repealed.

SECTION III

This Ordinance shall be in full force and effect from and after its adoption.

This the 22nd day of October, 1984.

AGENDA #8

MEMORANDUM

TO: Mayor and Council

FROM: David R. Taylor, Town Manager

SUBJECT: Proposed Water Conservation Ordinance

DATE: October 8, 1984

Attached for your consideration is a revised water conservation ordinance prepared by the Orange Water and Sewer Authority.

An issue paper by the OWASA staff, a copy of the present ordinance, and a cover letter from the Executive Director of OWASA are also attached. A representative of the OWASA administration will be prepared to make a presentation at the meeting Monday night.

Proposed Changes

Two key changes proposed by OWASA are:

- Earlier "trigger levels" for imposing restrictions when the level of University Lake drops:

Stage	Lake Level at which restrictions are triggered Under Present Ordinance	Usable Water Storage	Recommended Trigger Level	Usable Water Storage
Alert - Stage I	36" Below	350 MG	24" Below	400 MG
Warning II	48" Below	300 MG	36" Below	350 MG
Danger III	72" Below	200 MG	54" Below	275 MG
Emergency IV	96" Below	124 MG	72" Below	200 MG
Crisis V-	132" Below	25 MG	96" Below	125 MG

(MG = million gallons)

- Under Stage II (Warning) restrictions, Chapel Hill residents south of Franklin Street and Durham Boulevard would be allowed to water lawns and gardens only between 6 and 9 am on Saturdays.

  Residents to the north would be allowed to do this watering only between 6 and 9 am on Sundays.

  The Town's ordinance now allows this watering Town-wide under Stage II conditions between 4 and 9 pm on Saturdays. The change is intended to even out demand and thereby reduce the risk of sharp increases in water demand.

The OWASA staff's issue paper reviews the changes in more detail.

Discussion

Average treated water use has increased from 4.71 MGD when the present ordinance was adopted in 1977 to about 6.0 MGD in 1984.

Although the OWASA system appears likely to begin drawing water from a temporary dam at Cane Creek by 1986, we think that the proposed restrictions are reasonable and prudent, even if they do not become necessary.

Recommendation by OWASA Board of Directors: That Council adopt the following ordinance.

Manager's Recommendation: That Council adopt the following ordinance.

APPENDIX B

REGRESSION ANALYSIS ON MONTHLY STREAMFLOW VALUES

The first model investigated the effect of the seasonal dummy variable on both the intercept and slope of the relationship:

$$CC = B0 + B1 * Summer + B2 * FR + B3 * (Summer \cdot FR)$$

where: CC = monthly inflow from Cane Creek near Teer, in cfs·month

Summer = 1, for August, September, and October

= 0, for November, December, and January through July

FR = monthly inflow from Flat River at Bahama, in cfs·month

Bi = regression coefficient

(Summer·FR) = the shift in the monthly inflow from Flat River at Bahama due to summer variation in flows

Regression Results:
Ordinary Least Squares

Dependent Variable	CC	Number of Observations	144
Mean of Dependant Variable	894.21	Standard Deviation of Dep. Var.	969.20
Durbin Watson Statistic	1.671	Estimated Autocorrelation	0.165
Standard Error of Regression	492.77	Sum of Squared Residuals	0.340E+08
Total Variation	0.134E+09	Regression Variation	0.100E+09
Regression Degrees of Freedom	3	Residual Degrees of Freedom	140
R - Squared	0.747	Adjusted R - Squared	0.742
F (3,140)	137.73	Prob. Value for F	0.0000

Variable	Coefficient	Std. Error	t-ratio	Prob t>x	Mean of X	Std. Dev. of X
Constant	56.8874	74.44	0.764	0.4460		
Summer	21.1498	121.7	0.174	0.8622	0.250	0.434
FR	0.2375	0.132E-01	18.1	0.0000	3798.75	3710.96
Summer·FR	-0.131	0.269E-01	-4.884	0.0000	536.57	1992.35

The regression was repeated on the final model in which the constant term and the dummy variable, Summer, were excluded because they are not statistically significant:

$$CC = B2 * FR + B3 * (Summer \cdot FR)$$

Regression Results:
Ordinary Least Squares

Dependent Variable	CC	Number of Observations	144
Mean of Dependant Variable	894.21	Standard Deviation of Dep. Var.	969.20
Durbin Watson Statistic	1.673	Estimated Autocorrelation	0.164
Standard Error of Regression	491.45	Sum of Squared Residuals	0.343E+08
Total Variation	0.134E+09	Regression Variation	0.100E+09
Regression Degrees of Freedom	1	Residual Degrees of Freedom	142
R - Squared	0.745	Adjusted R - Squared	0.743
F (3,140)	414.18	Prob. Value for F	0.0000

Variable	Coefficient	Std. Error	t-ratio	Prob t>x	Mean of X	Std. Dev. of X
FR	0.2453	0.838E-02	29.272	0.0000	3798.75	3710.96
Summer·FR	-0.131	0.216E-01	-5.976	0.0000	536.57	1992.35

Both of the coeffients are significant in this model and the R-square value is acceptable.

Thus the final model used to obtain the inflows was:

$$CC = 0.245 \cdot FR \qquad \text{January - July, November, December}$$

$$CC = 0.116 \cdot FR \qquad \text{August, September, October}$$

(Speight, 1994)