School of Civil and
Environmental Engineering

A Reservoir Control Model for the Acheloos River

Aris P. Georgakakos
Huaming Yao
Yongqing Yu
Konstantinos G. Noutsopoulos

School of Civil and Environmental Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0355

National Technical University of Athens

Greek Ministry of Public Works

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Developed by

Aris P. Georgakakos
Principal Investigator

Huaming Yao
Post-Doctoral Fellow

Yongqing Yu
Graduate Research Assistant

Konstantinos G. Noutsopoulos
Graduate Research Assistant

School of Civil and Environmental Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0355

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CONTENTS

CHAPTER 1

INTRODUCTION

The Acheloos river (Figure 1.1) is located in western Greece and is a major water resource for agricultural and municipal water supply, flood control, hydropower generation, and environmental and ecosystem management. In sharp contrast to the Acheloos basin, the adjacent region of Thessalia (in central Greece) suffers frequently from droughts, diminishing water supplies, and ecosystem degradation. Concerned with the long-term water sustainability of Thessalia (a key agricultural region for the national economy), the Greek Government is considering augmenting its water supplies via a water diversion from the Upper Acheloos basin. As with most interbasin water transfers, this plan is bound to accrue both benefits and costs.

A preliminary study has indicated that the diversion would significantly improve the situation in Thessalia. More specifically, the water transfer would stabilize the declining groundwater levels, provide for adequate municipal and agricultural water supply, reverse the population relocation trends, upgrade the riverine ecosystems, and increase hydropower generation. On the other hand, the diversion would impact hydropower generation in the Acheloos River and would potentially strain agricultural water supplies and ecosystem management in that basin. At the national level, the benefits appear to outweigh the costs, but detailed studies are needed to effectively quantify the diversion impacts.

In view of this background, the purpose of this study is to assess the effects of the water diversion to the Acheloos River basin. Specifically, the goal is to develop a mathematical model of the Acheloos reservoir system and use it to quantify the anticipated reductions in hydropower generation and water supply reliability for various diversion scenarios. The model includes a control (i.e., optimization) and a control-simulation component. The purpose of the control model is to develop optimal reservoir operation policies, while that of the control-simulation model is to evaluate the performance of these policies over the historical inflow record.

This report includes five chapters and one appendix. In the following chapter, we give a short overview of the Acheloos reservoir system and discuss the data used in the study. In Chapter 3, we introduce the control model formulation, discuss our modeling assumptions, and describe the optimization philosophy. In Chapter 4, we present and elaborate on the model results, and in Chapter 5 summarize the conclusions and provide several recommendations for future investigations. Lastly, in the appendix, we include various reservoir characteristic curves and their analytical approximations.

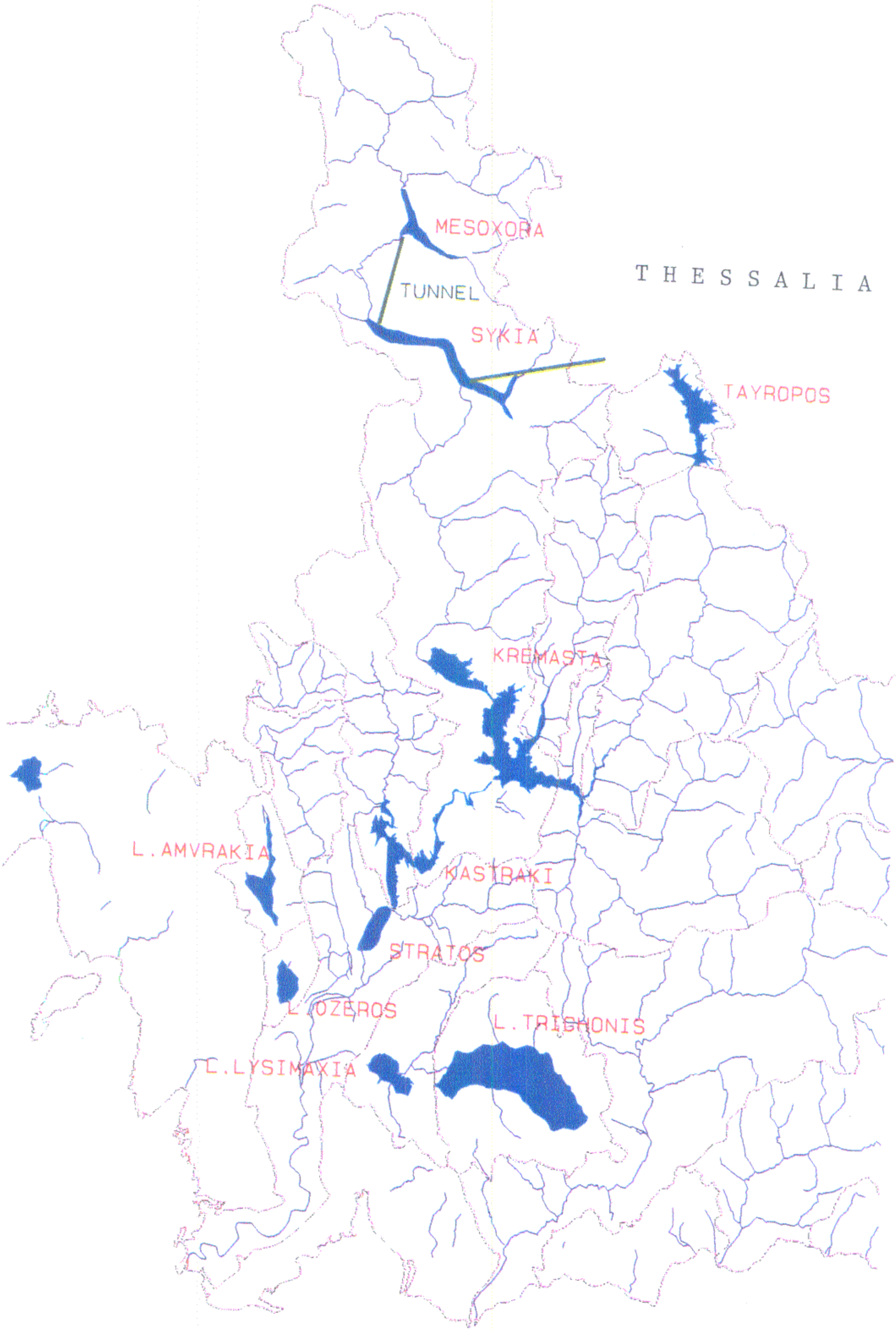

Figure 1.1: The Acheloos River Basin

CHAPTER 2

THE ACHELOOS RESERVOIR SYSTEM

The Acheloos River basin (Figure 1.1) currently includes four reservoirs (Kremasta, Kastraki, Tavropos, and Stratos), while two other projects (Mesohora and Sykia) are presently under construction. Of the existing reservoirs, the largest is Kremasta with a total storage of 4,500x10^6 cubic meters, whereas Kastraki, Tavropos, and Stratos are smaller projects with a combined storage of less than 1,500x10^6 cubic meters. The proposed water diversion to Thessalia would take place from the Upper Acheloos (Sykia) and would not affect the inflows to Tavropos. For this reason, this study focuses on the reservoir cascade consisting of Kremasta, Kastraki, and Stratos. The conservation storage of these three reservoirs is used to support water supply, hydropower generation, and environmental protection and extends over the ranges reported in Table 2.1.

Table 2.1: Ranges of Conservation Storage

	Minimum		Maximum	
Reservoir	Storage (10^9 m^3)	Elevation (m)	Storage (10^9 m^3)	Elevation (m)
Kremasta	999	227	4500	282
Kastraki	750	142	800	144.2
Stratos	60	67	70.2	68.6

Beyond the conservation storage, each reservoir includes a flood storage zone, in anticipation of major floods. The flood storage free board is two meters at Kremasta, 5.8 meters at Kastraki, and 0.4 meters at Stratos. Average seepage losses amount to 6 m^3/sec at Kremasta and 4 m^3/sec at Stratos, while at Kastraki, they are negligible. Other reservoir data, including elevation versus storage and area versus storage curves, and their analytical approximations, are included in Appendix A. All three projects have hydro electric generation units, the number and capacities of which are shown on Table 2.2.

Table 2.2: Hydroelectric Plant Characteristics

Reservoir	(Number of Units) x (Installed Capacity - MW)
Kremasta	4 x 109 = 436
Kastraki	4 x 80 = 320
Stratos	2 x 75 + 2 x 3 = 156

An approximate relationship between power generation, reservoir elevation, and turbine discharge is provided by the specific generation efficiency curves included in Appendix A. For lack of more detailed data, these relationships are used herein to model power generation at the monthly time scale.

Figures 2.1, 2.2, and 2.3 respectively summarize the monthly statistics of the reservoir inflows (local drainage basins) at Kremasta, Kastraki, and Stratos. (The inflows at Stratos are estimated based on those at Kastraki.) A correlation analysis of the Kremasta inflows indicates that the flows exhibit weak monthly correlations. The previous statistics are based on a 44-year record extending from 1951 to 1994. Furthermore, Figures 2.4 and 2.5 report the statistics of the (evaporation-rainfall) rates at Kremasta and Kastraki based on a 31-year record (1961-1991). The statistics for Stratos are assumed identical to those of Kastraki.

Except for energy generation and flood protection, the Acheloos reservoir system is expected to provide water for irrigation and maintain sufficient in stream flows to preserve environmental quality. Irrigation withdrawals amount to 35 m^3/sec during May through September, while 21 m^3/sec are mandated throughout the year for environmental preservation. Both of these requirements apply downstream of Stratos. Thus, the minimum release from Stratos is 56 m^3/sec for May through September and 21 m^3/sec for the rest of the year.

Lastly, the proposed diversion of Acheloos water to the neighboring region of Thessalia is planned to take place upstream of Kremasta. The amount of the diversion is estimated at 600 million cubic meters annually, with the seasonal distribution shown on Table 2.3.

Table 2.3: Seasonal Distribution of the Proposed Thessalia Diversion

Month	Jan.-Mar.	April	May	June	July	Aug.	Sep.	Oct.-Dec.
%	0	5	11	23.6	30.2	26.4	3.8	0

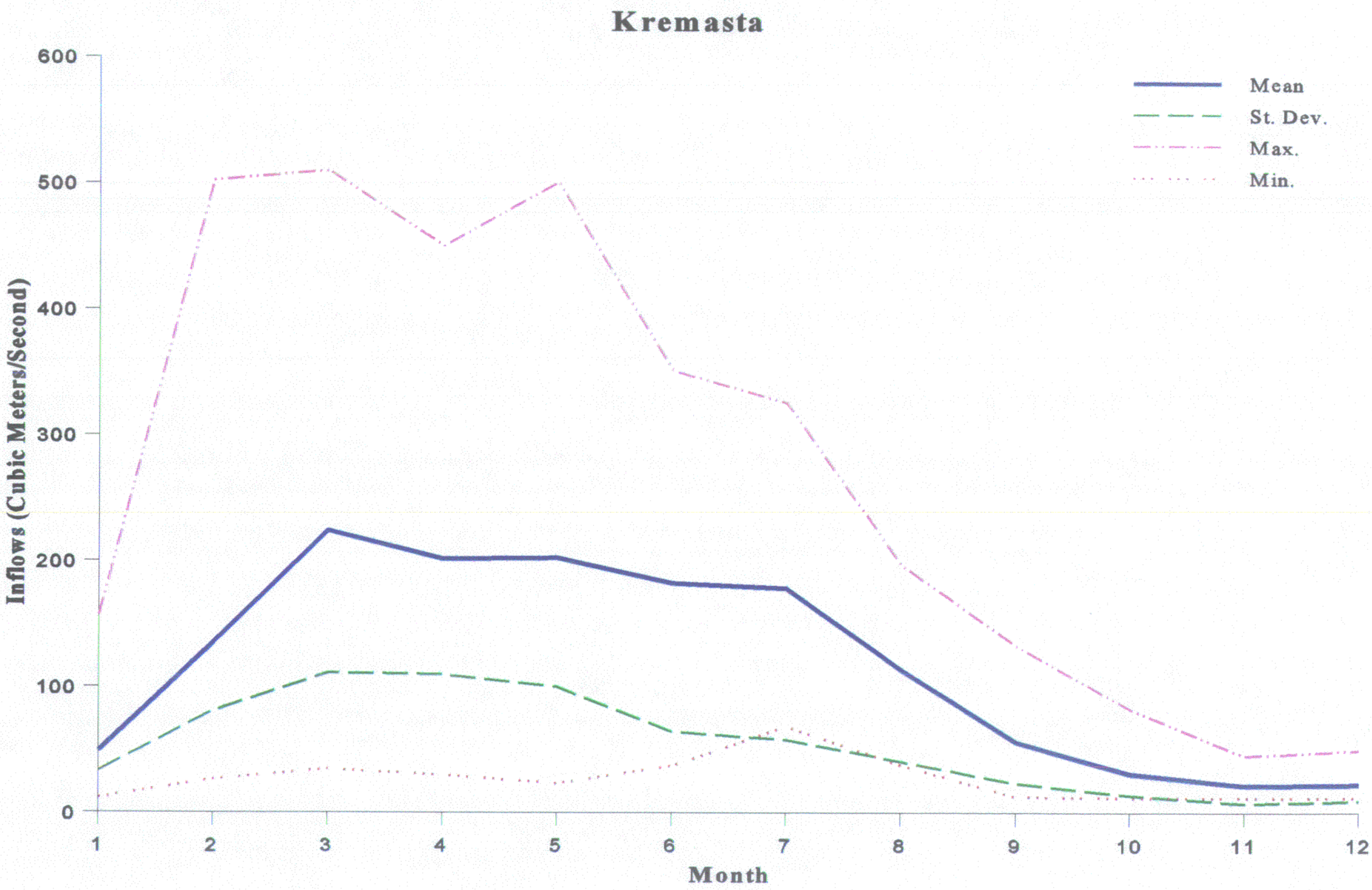

Figure 2.1: Statistics of Kremasta Inflows

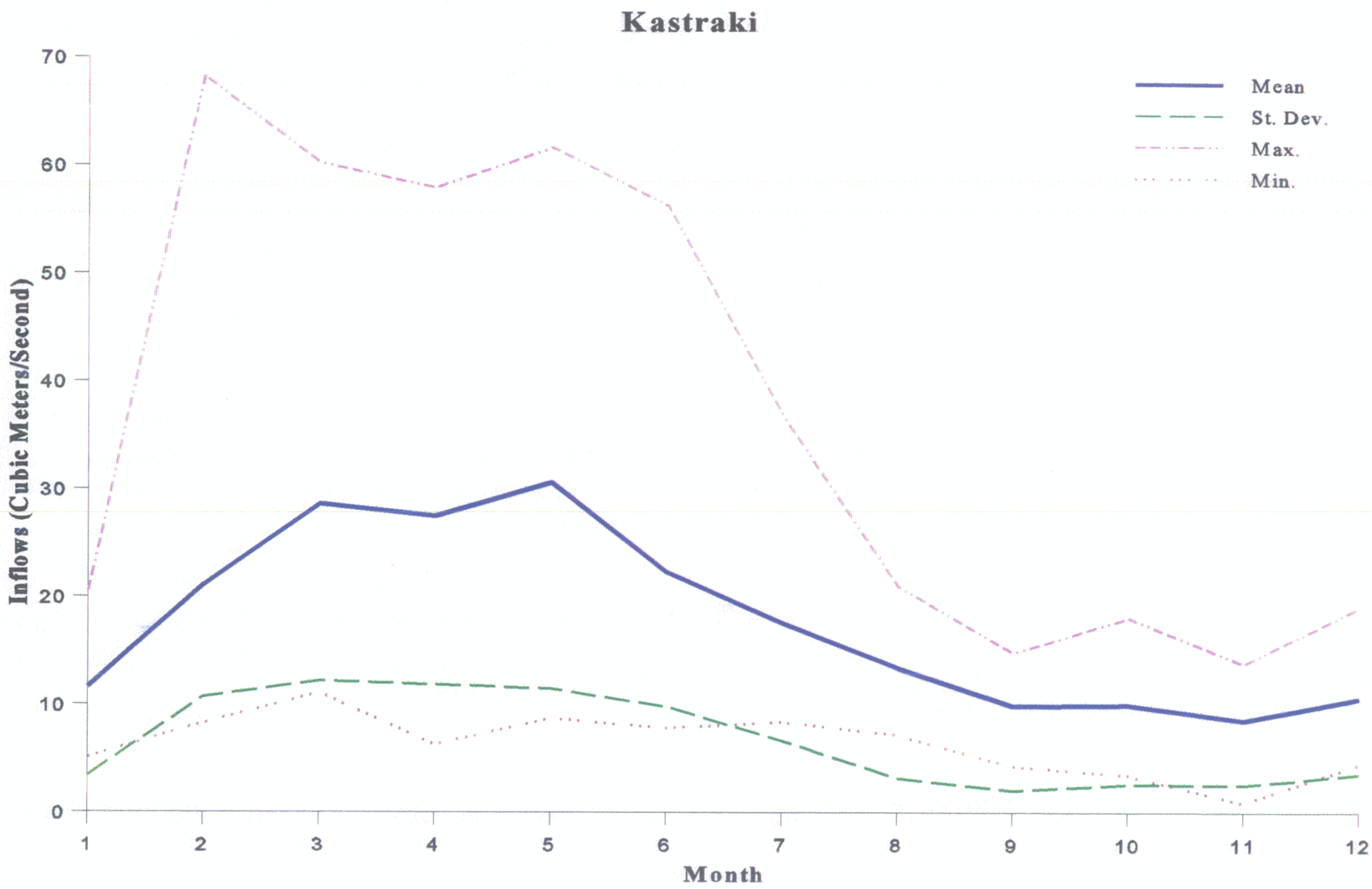

Figure 2.2: Statistics of Kastraki Inflows

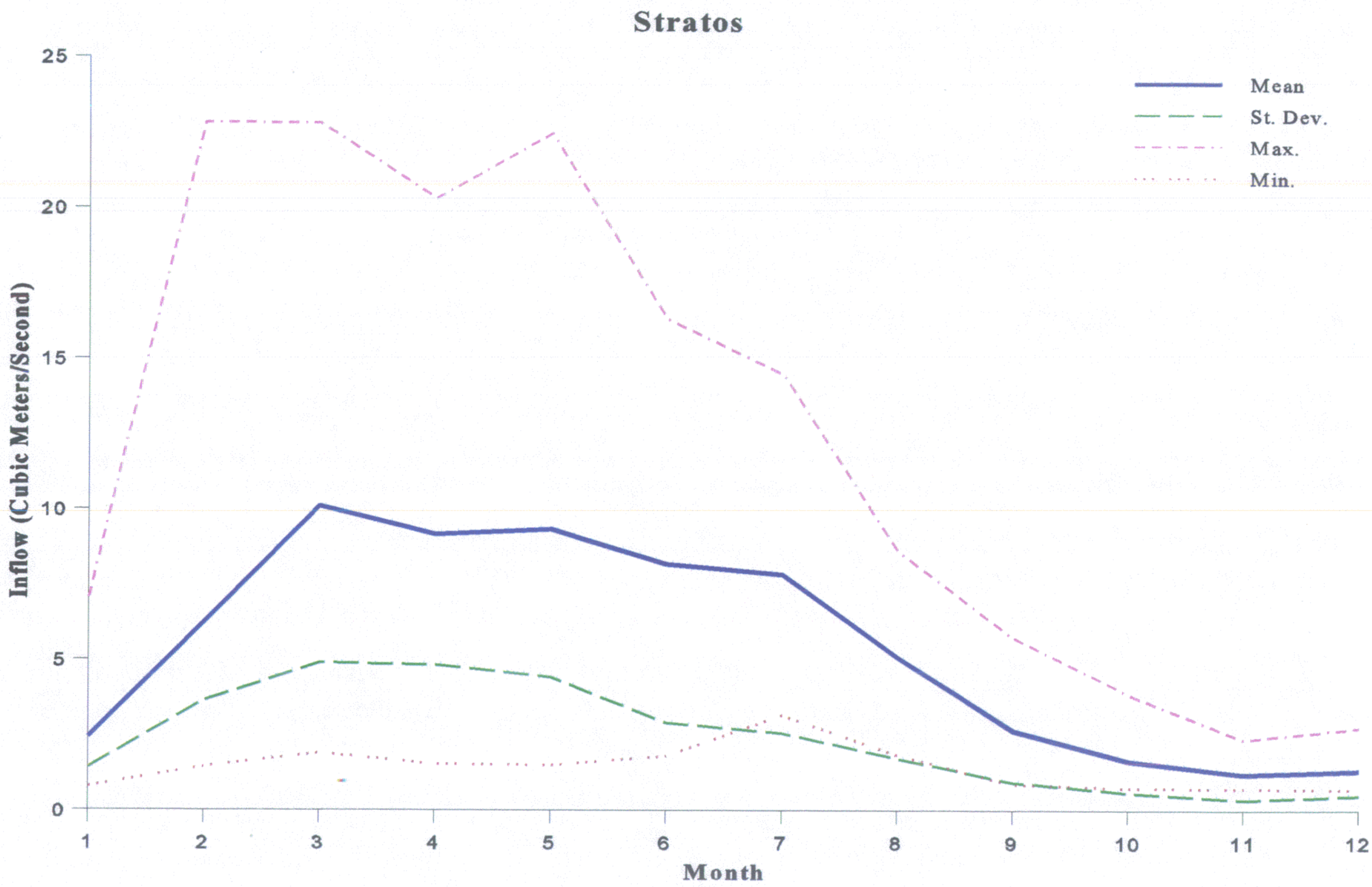

Figure 2.3: Statistics of Stratos Inflows

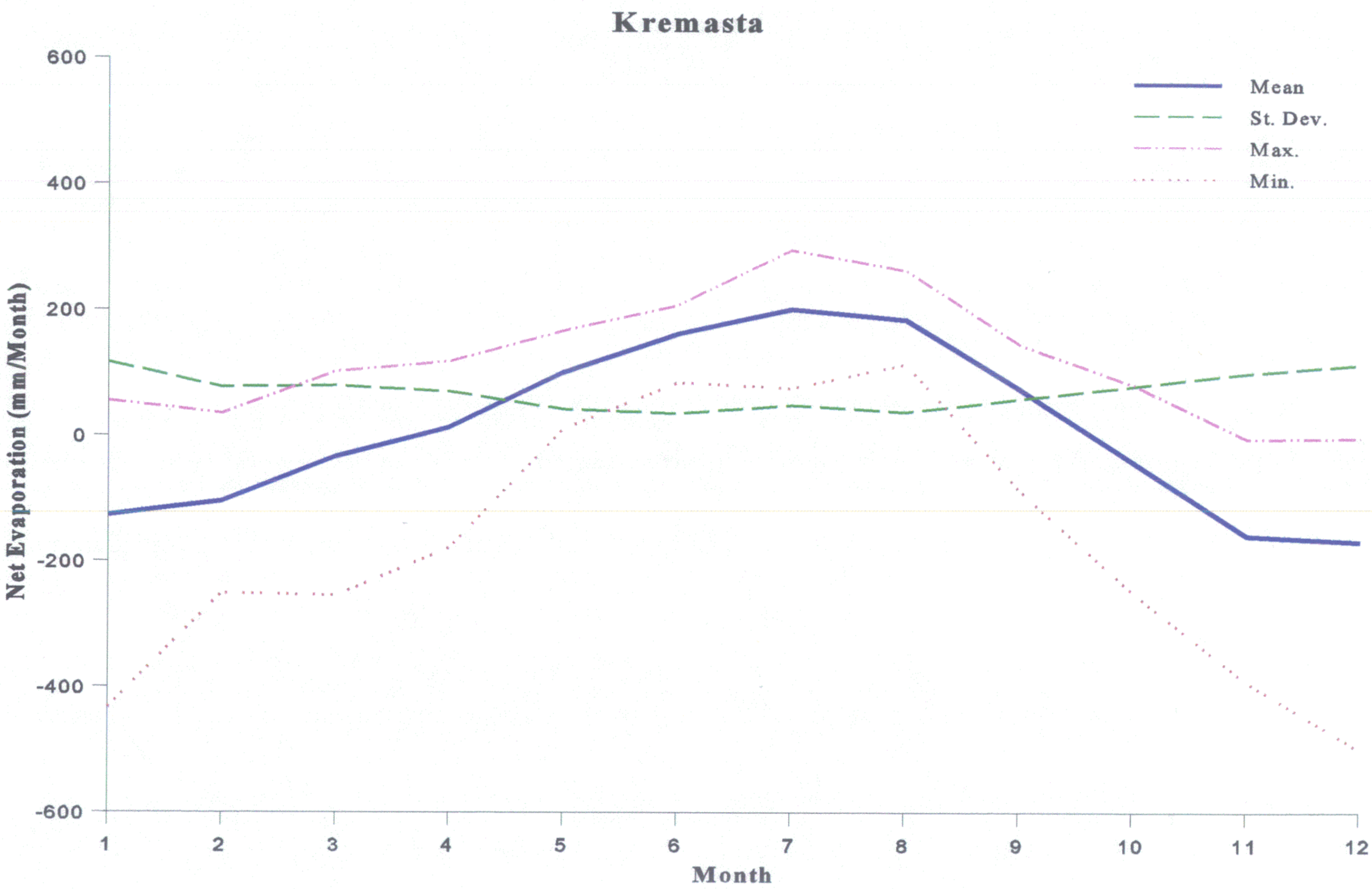

Figure 2.4: Statistics of (Evaporation-Rainfall) at Kremasta

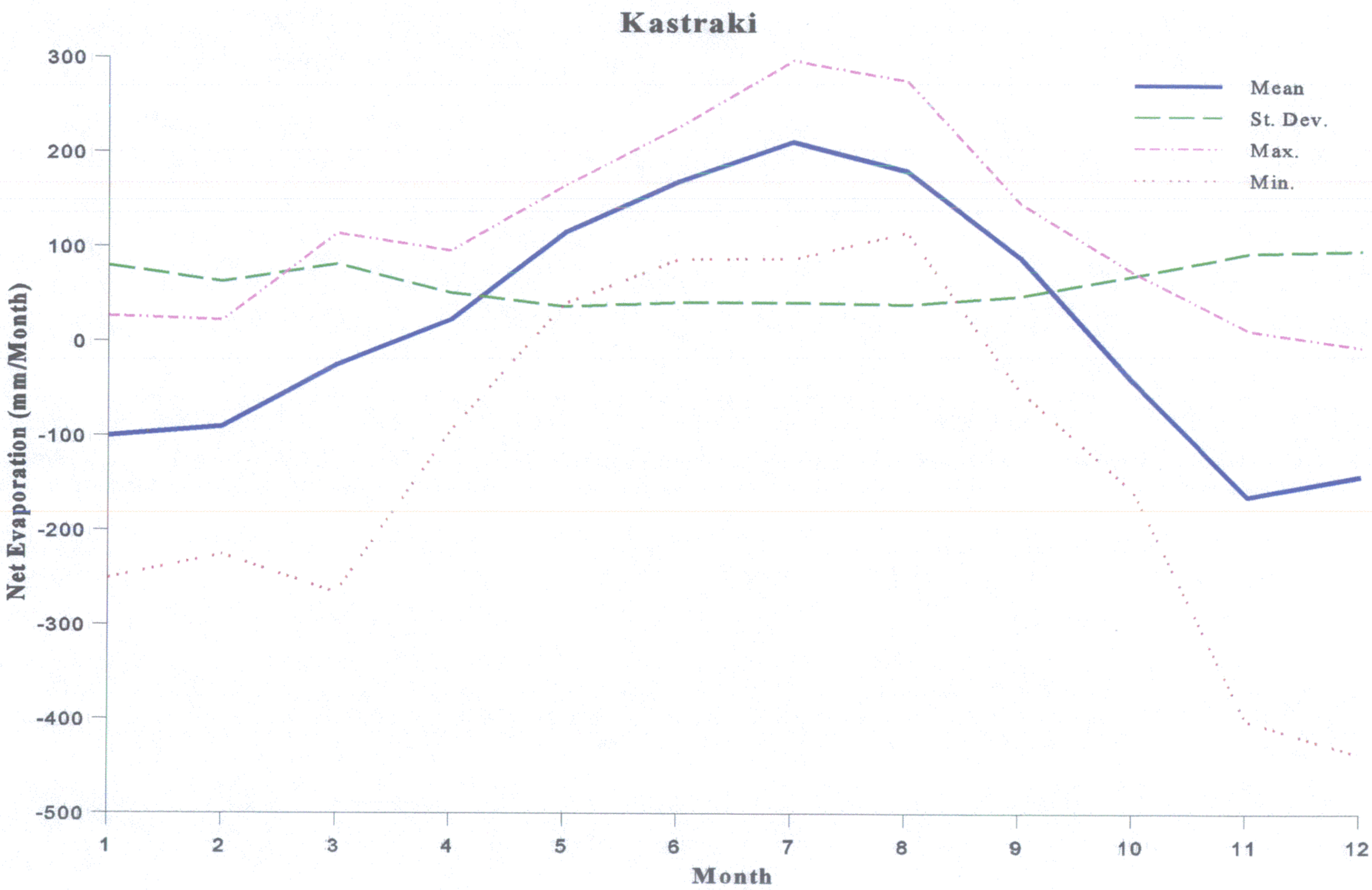

Figure 2.5: Statistics of (Evaporation-Rainfall) at Kastraki

CHAPTER 3

CONTROL MODEL

3.1 Formulation

3.1.1 System Dynamics

The Acheloos reservoir cascade is modeled by the following water balance relationships:

$$\begin{aligned} S_1(k+1) &= S_1(k) - e_1(k)A_1[S_1(k)] - u_1(k) + w_1(k) - L_1(k) - D(k) , \\ S_2(k+1) &= S_2(k) - e_2(k)A_2[S_2(k)] - u_2(k) + u_1(k) + w_2(k) - L_2(k) , \\ S_3(k+1) &= S_3(k) - e_3(k)A_3[S_3(k)] - u_3(k) + u_2(k) + w_3(k) - L_3(k) , \\ k &= 0,1,\ldots,N-1 , \end{aligned} \tag{3.1}$$

where the subscripts $i = 1, 2, 3$ respectively denote quantities pertaining to Kremasta, Kastraki, and Stratos; k is the discretization time interval corresponding to one month; $S_i(k)$ is the storage of the ith reservoir at the beginning of the month; $e_i(k)$ is the evaporation rate; $A_i[S_i(k)]$ is the reservoir area versus storage function; $u_i(k)$ is the release volume; $w_i(k)$ is the inflow volume; $L_i(k)$ is the water loss; D(k) is the planned water diversion; and N are the months of the control horizon. The characteristics of the inflow volumes, evaporation rates, area versus storage functions, reservoir losses, and of the planned diversion have been described in the previous chapter.

Storage and release variables are constrained to be within certain ranges as follows:

$$\begin{aligned} S_i^{\min}(k) &\le S_i(k) \le S_i^{\max}(k) , \\ u_i^{\min}(k) &\le u_i(k) \le u_i^{\max}(k) , \\ k &= 0,1,\ldots,N . \end{aligned} \tag{3.2}$$

The upper and lower storage limits in (3.2) correspond to the reservoir conservation storage zones reported in the previous chapter. (Flood storage is not included in the controllable storage range because the study uses a monthly time discretization.) The lower release limit for Kremasta and Kastraki are zero, while for Stratos it is equal to 147 million cubic meters per month for May through September and 55 million cubic meters per month for the rest of the year (as mandated by environmental and water supply requirements). The upper release bounds are determined based on the hydro plant capacity and the specific power generation curve (reported in Chapter 2 and Appendix A).

In view of the inflow uncertainty, storage constraints are more properly expressed in a probabilistic form:

$$\begin{aligned}&Prob[S_i^{\min}(k) \le S_i(k)] \le \pi_i^{\min}(k)\\ &Prob[S_i(k) \le S_i^{\max}(k)] \ge \pi_i^{\max}(k) \qquad \textbf{(3.3)}\\ &i = 1,2,3, \quad k = 0,1,\ldots,N,\end{aligned}$$

where $\pi^{\min}$ and $\pi^{\max}$ are reliability levels. These levels as well as the upper and lower storage and release thresholds are denoted here as time-varying, but are usually time-invariant.

Equations (3.1), (3.2), and (3.3) summarize the reservoir system model. In control systems terminology, reservoir storages are the state variables, and releases are the control variables. The goal of the control procedure is to identify the release sequences $\{u_i^*(k), i=1,2,3; k=0,1,\ldots,N-1\}$ such that system objectives and constraints are met successfully. The element of the formulation that brings this about and also measures the success of the various operational alternatives is the performance index which we discuss next.

3.1.2 Performance Index

The goal of the control procedure is to maximize the monthly dependable power capacity of the Acheloos reservoir system, while meeting its environmental and water supply demands. To achieve this objective, we minimize the following performance index:

$$J = E\left\{ \sum_{k=0}^{N-1} \left\{ \alpha \exp\left[-\frac{[P_1(k)+P_2(k)+P_3(k)] - P^*}{T_p}\right] + \beta \left[\sum_{i=1}^{3} \exp\left[-\frac{H_i^{\max} - H_i(S_i(k))}{T_H}\right] + \exp\left[-\frac{H_i(S_i(k)) - H_i^{\min}}{T_H}\right] \right] \right\} \right\}. \tag{3.4}$$

In the above, E{ } denotes expectation of the quantity in the brackets with respect to the joint probability distribution of the reservoir inflows. This expectation is simplified by the fact that reservoir inflows exhibit only weak autocorrelation and can, therefore, be assumed to be statistically independent. In the first term of the performance index, $P_1(k)$, $P_2(k)$, and $P_3(k)$ denote the power generation levels of Kremasta, Kastraki, and Stratos, and P^* is the dependable capacity target. (The P_i's are functions of turbine releases and reservoir elevations as discussed in the previous chapter.) This term is intended to penalize failures to meet the power target P^* at any time during the control horizon, by imposing an increasingly higher penalty as $P(k) = P_1(k) + P_2(k) + P_3(k)$ falls short of P^*, while becoming negligible as $P(k)$ exceeds P^*. The form of this penalty function is shown on Figure 3.1.

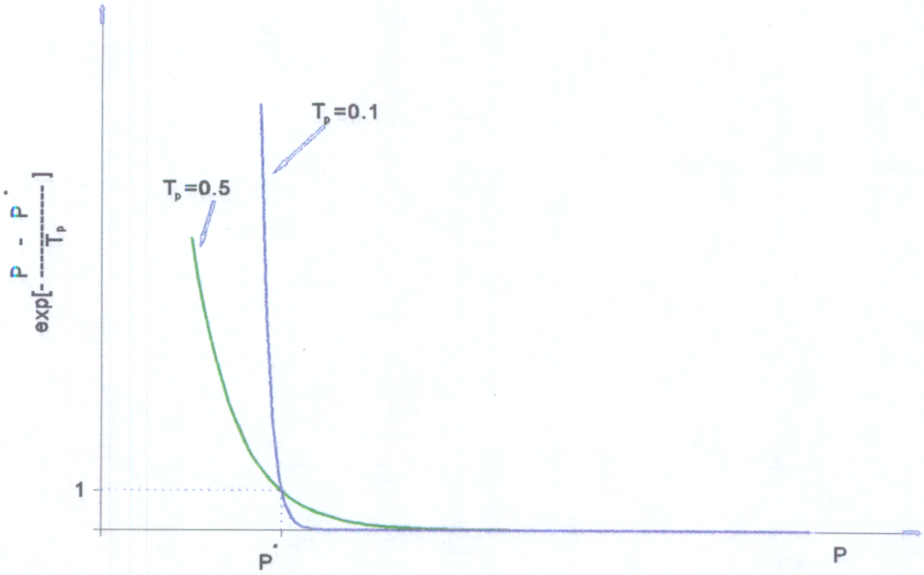

Figure 3.1: Form of the Power Penalty Term

Parameter T_p may be used to adjust the curvature of the exponential function. Smaller T_p values are associated with steeper curvature but also may cause numerical overflow during the optimization process. Thus, the correct specification of this parameter may require some experimentation. A reliable procedure is to start the optimization process with a large value (e.g., $T_p = 1$), and subsequently reduce it to the level that forces the satisfaction of this constraint (e.g., $T_p = 0.1$).

The second term (Figure 3.2) is intended to keep reservoir elevations within their respective bounds, $[H^{min}, H^{max}]$.

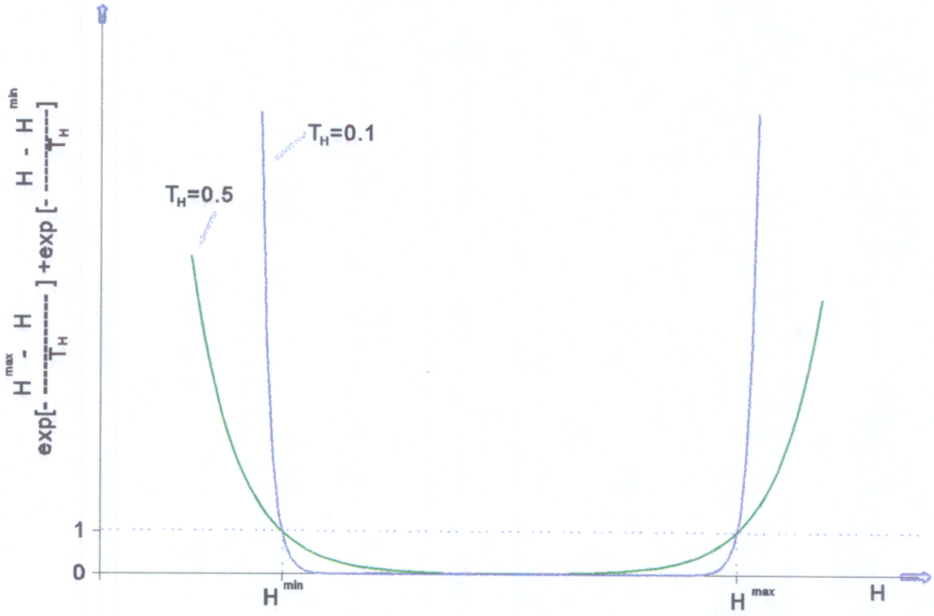

Figure 3.2: Form of the Reservoir Elevation Penalty Terms

Penalty parameters α and β, may be used to introduce priorities in the performance index terms. In this case, these parameters should be determined such that the second term is dominant. The logic is to determine feasible sequences (2nd term) guaranteed to exceed a certain power target (1st term). We note that the previous barrier functions have the structural advantage of being analytical and yet delimit with desirable accuracy the feasible storage, release, or power regions.

To facilitate the ELQG iteration process, the performance index is expanded to include three additional terms:

$$
\begin{aligned}
J = E\{ \sum_{k=0}^{N-1} \{ & \alpha \exp[-\frac{P(k)-P^*}{T_p}] \\
& + \beta \left[\sum_{i=1}^{3} \exp[-\frac{H_i^{\max}-H_i(S_i(k))}{T_H}] + \exp[-\frac{H_i(S_i(k))-H_i^{\min}}{T_H}] \right] \qquad \textbf{(3.5)} \\
& + \gamma \sum_{i=1}^{3} [H_i(S_i(k))-H_i^{\max}]^2 + \delta \sum_{i=1}^{3} [P_i(k)-P_i^*]^2 \} + \epsilon \sum_{i=1}^{3} [H_i(S_i(N))-H_i^{\max}]^2 \} .
\end{aligned}
$$

The third and fifth terms penalize reservoir elevation deviations from full storage, while the fourth term penalizes power deviations from the target values P_i^*. The rational of the third and fourth terms is to maximize turbine efficiency by maintaining reservoir elevations as high as possible (without causing spillage). The power targets P_i^* are herein set equal to zero to reflect a water conservation objective. Namely, the goal is to maximize the system dependable power capacity by releasing as little as possible. In this sense, the effect of all new terms is synergistic-- they all contribute to maximizing the efficiency of power generation. Moreover, another reason for including these "tracking" terms is to add convexity to the problem and improve the convergence rate. Thus, although the new terms are smaller in magnitude than the original two terms, they create the mathematical framework (positive definiteness and controllability conditions) that is necessary for the success of the optimization process. The selection of parameters γ, δ, and ϵ should reflect this perspective. Namely, their values should be at least one or two orders of magnitude smaller than those of α and β.

3.2 ELQG Control Method

The control problem formulated in the previous section is solved using the Extended Linear Quadratic Gaussian (ELQG) control method which was originally introduced by *Georgakakos and Marks, 1987,* and further developed by *Georgakakos 1989, 1991, 1993,* and *Georgakakos et al., 1995a,b,c.* ELQG is an iterative optimization procedure starting from an initial control sequence $\{u_i(k);\ i=1,2,3;\ k=0,1,2,..,N-1\}$ and subsequently generating increasingly better sequences until convergence. Convergence is achieved when the value of the performance index cannot be reduced any further. ELQG is chosen because it is reliable, computationally efficient, and especially-suited for uncertain multi reservoir systems. For a complete discussion of this method, the reader is referred to the above-cited references. In what follows, we give a short account of the ELQG optimization procedure and features.

The system model presented in the previous sections includes three elements which can be expressed in the following general form:

i. System Dynamics:

$$\begin{aligned} S(k+1) &= f[S(k)] + \boldsymbol{B}\,u(k) + \boldsymbol{C}\,w(k) + d(k) \\ k &= 0,1,\ldots,N-1, \end{aligned} \tag{3.6}$$

ii. Constraints:

$$\begin{aligned} &Prob[S_i^{\min}(k) \le S_i(k)] \le \pi_i^{\min}(k) \\ &Prob[S_i(k) \le S_i^{\max}(k)] \ge \pi_i^{\max}(k) \\ &u_i^{\min}(k) \le u_i(k) \le u_i^{\max}(k)\ , \\ &i = 1,2,3, \quad k = 0,1,\ldots,N, \end{aligned} \tag{3.7}$$

iii. Performance index:

$$\underset{u(k),\,k=0,1,\ldots,N-1}{Minimize\ J} = E\left\{\sum_{k=0}^{N-1} g_k[S(k),u(k)] + g_N[S(N)]\right\}, \tag{3.8}$$

where S(k) and **u(k)** are the state and control vectors; **f[S(k)]**, **A**, **B**, and **C** are vector functions and coefficient matrices defined below; $g_k[\bullet]$ is the cost function associated with period k; g_N is the cost function associated with the terminal time; and N is the control horizon. (Bold type indicates vector or matrix quantities.)

$$S(k) = \begin{bmatrix} S_1(k) \\ S_2(k) \\ S_3(k) \end{bmatrix} \;,\; u(k) = \begin{bmatrix} u_1(k) \\ u_2(k) \\ u_3(k) \end{bmatrix} \;,\; d(k) = \begin{bmatrix} -D(k) - L_1(k) \\ -L_2(k) \\ -L_3(k) \end{bmatrix}$$

$$f[S(k)] = \begin{bmatrix} S_1(k) - e_1(k)A[S_1(k)] & 0 & 0 \\ 0 & S_2(k) - e_2(k)A[S_2(k)] & 0 \\ 0 & 0 & S_3(k) - e_3(k)A[S_3(k)] \end{bmatrix} \tag{3.9}$$

$$B = \begin{bmatrix} -1 & 0 & 0 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \;,\; C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The Extended Linear Quadratic Gaussian (ELQG) solution procedure starts with an initial control sequence $\{u^0(k),\ k = 0, 1, \ldots, N-1\}$ and the corresponding mean state sequence $\{\bar{S}^0(k),\ k = 0, 1, \ldots, N\}$:

$$\begin{aligned} \bar{S}^0(k+1) &= f[\bar{S}^0(k)] + B u^0(k) + C\bar{w}(k) + d(k) \;, \\ \bar{S}^0(0) &= S(0) = known, \\ k &= 0, 1, \ldots, N-1 \;, \end{aligned} \tag{3.10}$$

where $\bar{w}(k)$ represents mean inflow. The next step is to define a perturbation model valid around these nominal state and control sequences. This model describes the dynamic relationship of the state, control, and input vector perturbations,

$$\begin{aligned} \Delta S(k) &= S(k) - \bar{S}^0(k)\,, \quad k=0,1,\ldots,N, \\ \Delta u(k) &= u(k) - u^0(k)\,, \quad k=0,1,\ldots,N-1, \\ \Delta w(k) &= w(k) - \bar{w}(k)\,, \quad k=0,1,\ldots,N-1, \end{aligned} \tag{3.11}$$

and has the following form:

$$\begin{aligned} \Delta S(k+1) &= A(k)\,\Delta S(k) + B\,\Delta u(k) + C\,\Delta w(k)\,, \\ \Delta S(0) &= \mathbf{0}\,, \\ & k=0,1,\ldots,N-1\,, \end{aligned} \tag{3.12}$$

where **A(k)** is a time-varying coefficient matrix resulting from the linearization of function **f[S(k)]** around the nominal state sequences. More specifically, this matrix is defined as follows:

$$A(k) = \begin{bmatrix} 1 - e_1(k)\dfrac{\partial A_1[\bar{S}_1^0(k)]}{\partial S_1(k)} & 0 & 0 \\ 0 & 1 - e_2(k)\dfrac{\partial A_2[\bar{S}_2^0(k)]}{\partial S_2(k)} & 0 \\ 0 & 0 & 1 - e_3(k)\dfrac{\partial A_3[\bar{S}_3^0(k)]}{\partial S_3(k)} \end{bmatrix}, \tag{3.13}$$

where the derivative terms represent the derivatives of the area versus storage functions evaluated at the nominal storage sequences.

The performance index is also expressed in terms of the perturbation variables as follows:

$$J = E\{\sum_{k=0}^{N-1} [\frac{1}{2}\Delta S^T(k)\, Q_{ss}(k)\, \Delta S(k) + q_s^T(k)\, \Delta S(k)$$

$$+ \frac{1}{2}\Delta u^T(k)\, R_{uu}(k)\, \Delta u(k) + r_u^T(k)\, \Delta u(k) + \Delta u^T(k)\, Q_{us}(k)\, \Delta S(k)] \quad (3.14)$$

$$+ \frac{1}{2}\Delta S^T(N)\, Q_{ss}(N)\, \Delta S(N) + q_s^T(N)\, \Delta S(N)\}\ ,$$

where $\mathbf{Q}_{ss}(k)$, $\mathbf{q}_s(k)$, $\mathbf{R}_{uu}(k)$, $\mathbf{r}_u(k)$, $\mathbf{Q}_{us}(k)$ are coefficient matrices defining a quadratic approximation of the original performance index. These matrices include the first and second partial derivatives of the $g_k[\ ]$ and $g_N[\ ]$ functions with respect to the state and control variables evaluated at the nominal sequences.

The perturbation control problem defined above is next solved to generate an optimal control sequence $\{\Delta\mathbf{u}^*(k), k=0,1, ..., N-1\}$. This constitutes the optimization direction which defines the new nominal control sequence according to the following relationship:

$$u^{new}(k) = u^0(k) + \alpha\, \Delta u^*(k)\ ,\qquad k = 0,1,\ldots,N-1\ , \quad (3.15)$$

where α is the optimization step size. Some important features of the ELQG solution process are summarized below:

- The ELQG iterations are **(1)** analytically-based (the optimization directions are obtained by Riccati-like equations), **(2)** reliable (the iteration process is guaranteed to converge if the problem has a feasible solution), and **(3)** computationally efficient (convergence is fast). In fact, in the neighborhood of the optimum, it can be theoretically shown that the method converges at a quadratic rate.

- Control constraints are not included in the performance index as penalty terms but are handled *explicitly* through a Projected-Newton procedure. This has important computational efficiency implications as it allows for many constraints to enter or exit the binding control set at the same iteration. The optimization direction is then obtained in the space of the binding constraints.

- State constraints are handled through the barrier functions discussed in the previous section. This approach has proven to be reliable and computationally efficient, much more so than quadratic penalty or multiplier methods. Handling of the state constraints requires the characterization of the state probability density. This density is herein defined by its mean and covariance vector, respectively obtained by equations (3.10) and (3.16):

$$\begin{aligned} P_S(k+1) &= F(k)\, P_S(k)\, F^T(k) + C\, P_w(k)\, C^T , \\ F(k) &= A(k) - B\, D(k)\, L(k) , \\ k &= 0,1,\ldots,N-1 , \end{aligned} \tag{3.16}$$

where $\mathbf{P}_S(k)$ and $\mathbf{P}_w(k)$ are the state and input covariance matrices and $\{\mathbf{D}(k), \mathbf{L}(k), k=0,1,\ldots,N-1\}$ are control gains generated by the ELQG solution process. These gains represent a linear approximation of the true feedback laws and are used in the covariance computation to indicate that future decisions will take into consideration measurements of reservoir storage (feedback). The state mean and covariance are then used to construct a normal approximation of the state probability density and convert constraints (3.3) into deterministic equivalents on the storage mean:

$$\begin{aligned} &\xi_i^{\min}(k) \le \bar{S}_i(k) \le \xi_i^{\max}(k) , \\ &i = 1,2,3, \quad k = 0,1,\ldots,N, \end{aligned} \tag{3.17}$$

where $\{\xi_i^{\min}, \xi_i^{\max}\}$ are the mean storage levels such that

$$\begin{aligned} &Prob[S_i^{\min}(k) \le S_i(k)] = \pi_i^{\min}(k) \\ &Prob[S_i(k) \le S_i^{\max}(k)] = \pi_i^{\max}(k) \\ &i = 1,2,3, \quad k = 0,1,\ldots,N. \end{aligned} \tag{3.18}$$

The ELQG iterations continue until the value of the performance index (3.5) cannot be further reduced. At this point the process terminates, and the current nominal control sequence becomes the problem solution. Under convexity conditions (which are valid in this formulation), this solution is globally optimal. (Convexity can be tested by starting the optimization process from different initial control sequences and checking if convergence occurs at the same optimal sequence.) More details on the ELQG features can be found in the above-cited references. In the following section, we discuss several case studies with the Acheloos reservoir system.

CHAPTER 4

CASE STUDIES

4.1 Control Experiments

In this section, we present the results of two control model runs. The first applies to the case of no water diversion, while the other assumes that there is an annual water diversion of 600 x 10^6 m^3 apportioned monthly according to the percentages reported in Chapter 2. The length of the control horizon is 12 months starting June 1st. The objective is to secure a combined energy amount of at least 170 GWH per month from all three projects, without violating the elevation and release bounds by more than 5%. The minimum release from Stratos is 147 million cubic meters per month for May through September and 55.2 million cubic meters per month for the rest of the year. At the beginning of June, the water elevation is 256.6 meters at Kremasta, 143.5 meters at Kastraki, and 67.78 meters at Stratos. The inflow forecasts simply constitute by the historical monthly statistics reported in Chapter 2.

Figures 4.1, 4.2, and 4.3 show the results for the base case (no diversion scenario). The figures respectively depict the reservoir elevation sequences (the solid line corresponds to the mean storage values while the dashed lines delineate the 90% probability band), the optimal releases, and the associated energy generation amounts. For the first six months, all three elevation probability bands are within their feasible ranges. However, beyond that, the inflow uncertainty at Kastraki and Stratos is such that the bands saturate the elevation ranges and cannot be effectively controlled. In this part of the control horizon, the objective of the control model is to maintain the *mean* reservoir elevations within the feasible zone. This condition is not a limitation of the control model; it simply indicates that the operational ranges of Kastraki and Stratos are too small to fully control the inflows. On the other hand, Kremasta is large enough to always contain its 90% probability band. The energy sequences (Figure 4.3) show that the combined energy generation equals 170 GWH, although the generation of the individual reservoirs vary.

Figures 4.4, 4.5, and 4.6 show the results for the 600 x 10^6 m^3 diversion scenario. The graphs of the reservoir elevation sequences are similar to those of the previous case, but the releases and energy generation are quite different. The main difference is that the mean inflows during the first part of the control horizon (June to September) are reduced in accordance to the diversion schedule, with the consequence that the system can no longer meet its 170 GWH monthly generation target (while maintaining feasible Kremasta elevations). Consequently, reservoir releases as well as energy generation amounts are reduced vis-a-vis the no diversion scenario. In particular, during the first half of the control horizon (when water diversion is high), total energy generation barely reaches 130 GWH/month. Later on, as the diversion ceases, the system is again able to meet its 170 GWH/month energy target.

The previous case studies are intended to describe some of the characteristics of the optimal sequences determined by the control model. They also indicate that the diversion could potentially limit the ability of the reservoir system to maximize its energy generation. These, however, are hypothetical cases and cannot be used to make conclusive statements about the effect of the diversion. To address this question, one needs to simulate the system response with and without the diversion. This is taken up in the following section.

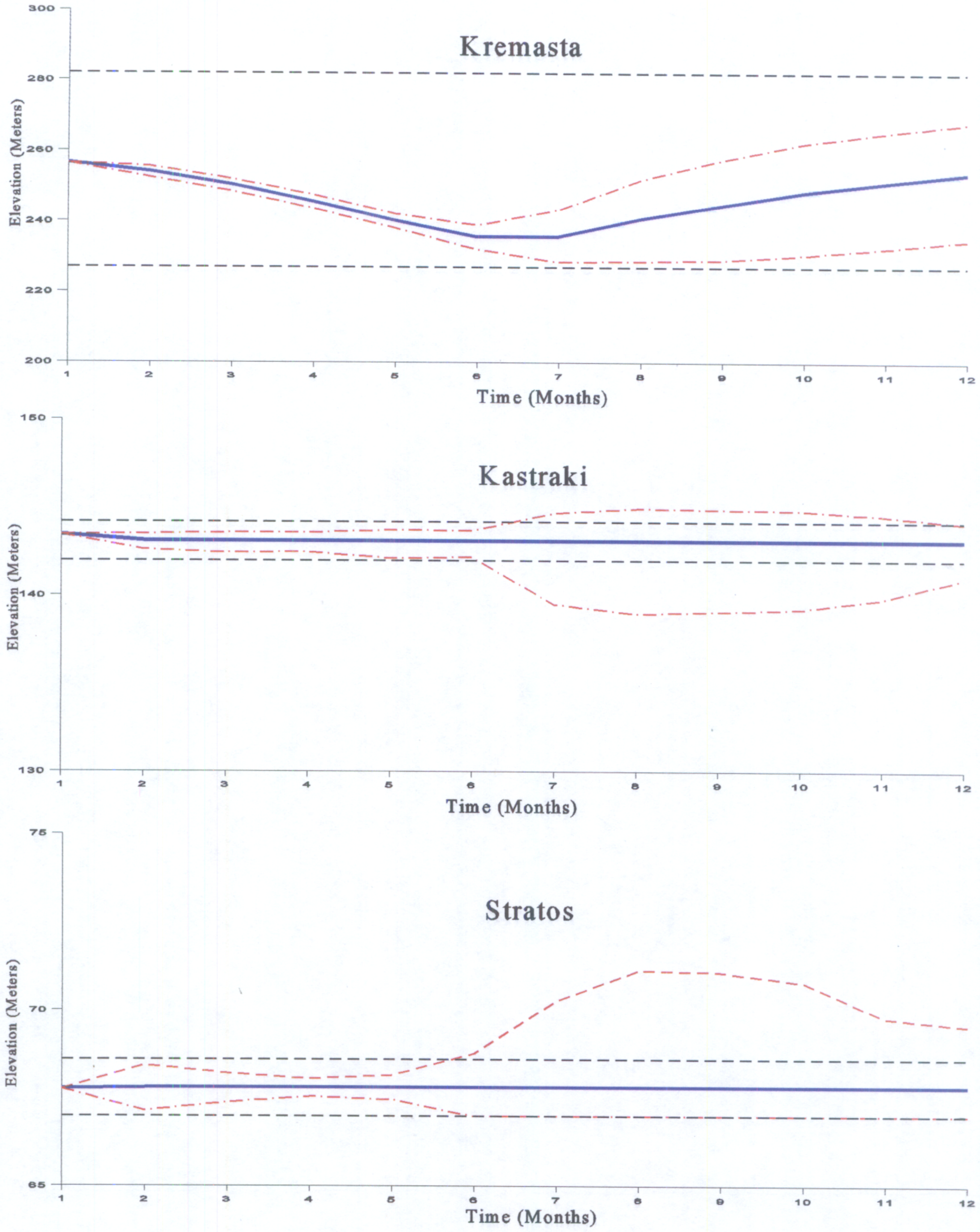

Figure 4.1: Control Model Results; Reservoir Elevations; Base Case

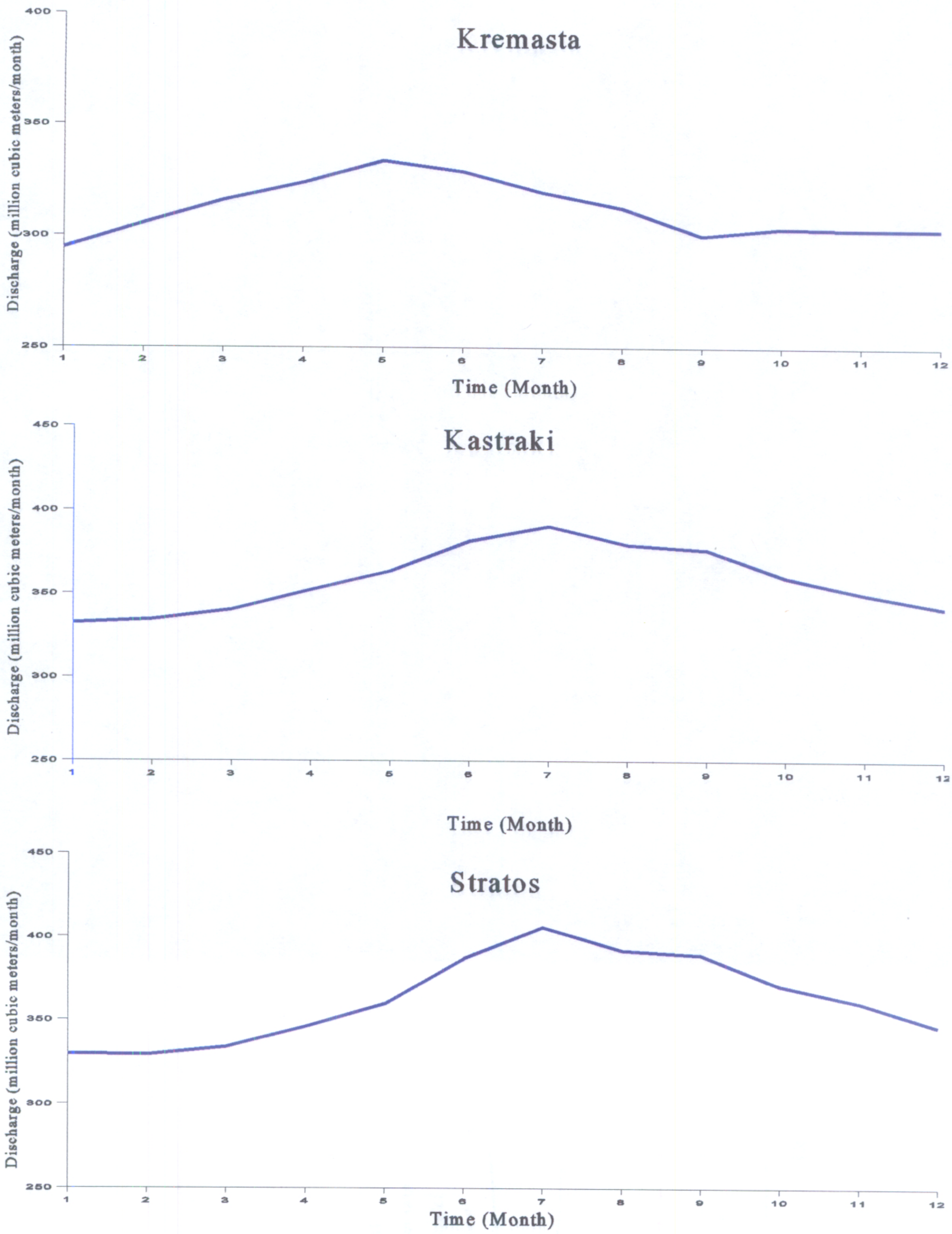

Figure 4.2: Control Model Results; Release Sequences; Base Case

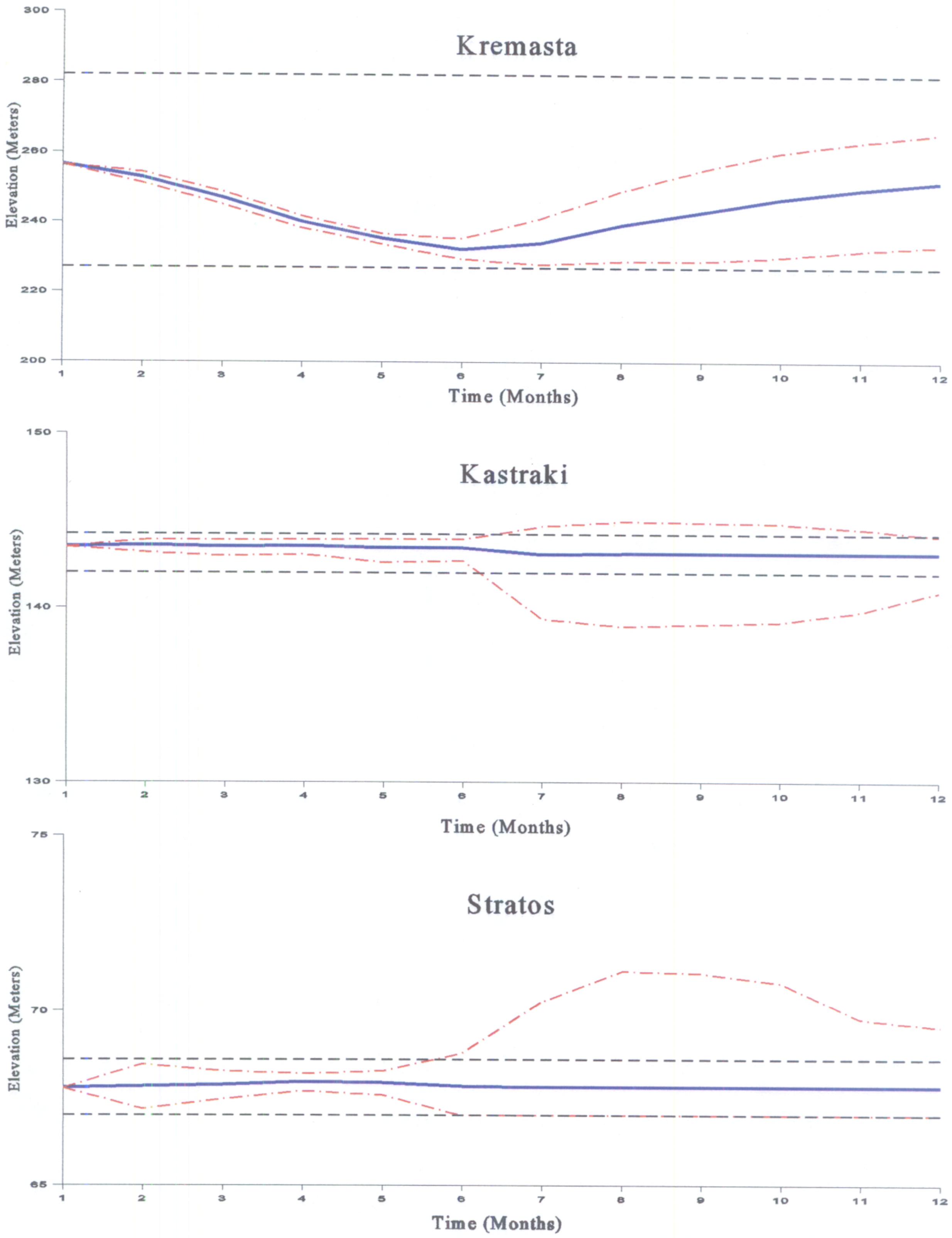

Figure 4.4: Control Model Results; Reservoir Elevations; Diversion Scenario

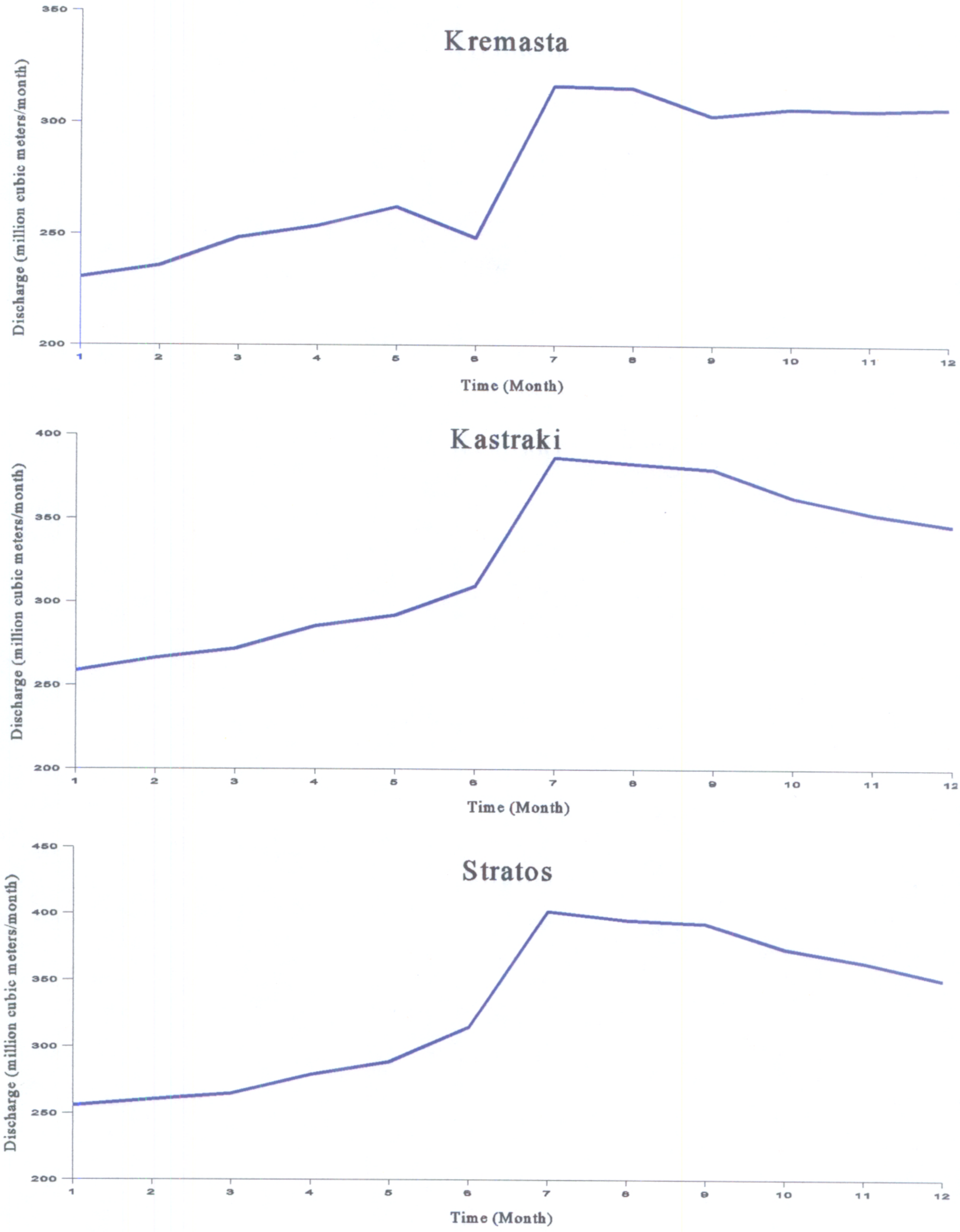

Figure 4.5: Control Model Results; Release Sequences; Diversion Scenario

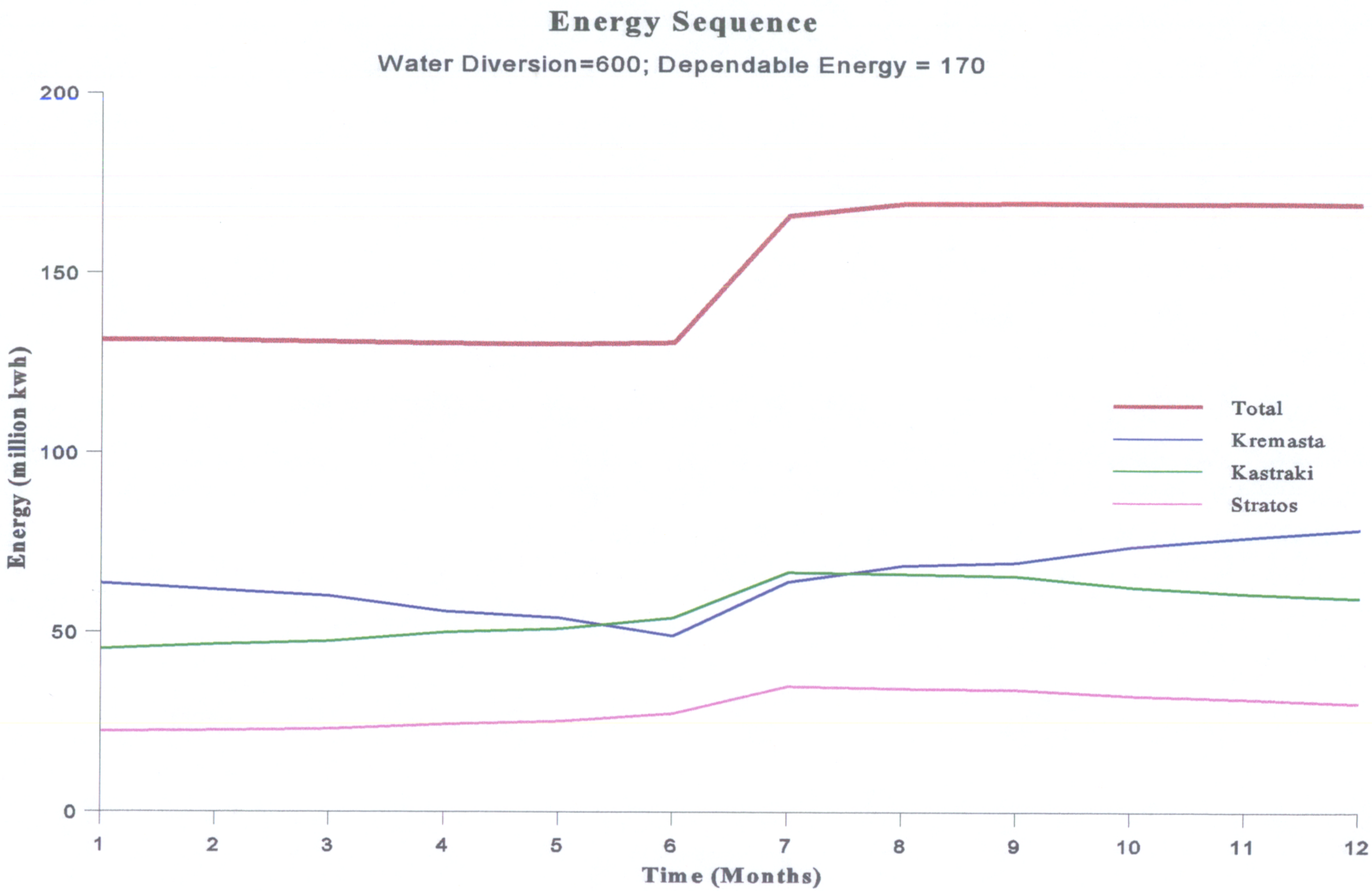

Figure 4.6: Control Model Results; Energy Sequences; Diversion Scenario

4.2 Control-Simulation Experiments

The purpose of the control-simulation experiments is to quantify the performance of the system under different diversion scenarios and with the operation guided by the control model. The basis for these experiments is the 44-year long monthly historical inflow record (1951-1994), and the control-simulation process is as follows: For each month of the historical record, the control model is activated first to generate the optimal reservoir release sequences as in the previous section. The control model parameters are the same as before (95% reliability for constraint violation, 12-month control horizon, and historical inflow statistics used as forecasts), with the only difference being the values of the initial reservoir elevations which are determined based on the results of the previous step. From the 12-month optimal release sequences, only the first month's optimal releases are actually implemented, and the system response is simulated using the historically observed inflows. If the optimal releases result in feasible end-of-the-month reservoir elevations, the program completes this control-simulation step, records these elevations along with the releases and the energy generation amounts, and repeats this process at the next month. Otherwise, appropriate release adjustments are made so that all reservoirs stay within their feasible ranges. This control-simulation process is repeated for 528 (= 44 x 12) months and results in a long series of simulated reservoir elevations, releases, and energy generation amounts. This series can then be analyzed to develop statistics of system performance and make comparisons.

The first control-simulation experiment corresponds to the base case scenario of zero diversion (Figures 4.7, 4.8, and 4.9). As indicated by the drawdown at Kremasta (Figure 4.7) and by the release sequences (Figure 4.8), the system experiences droughts toward the end of the simulation horizon, and on a few occasions it is unable to meet its water supply requirements. As expected, Kastraki and Stratos are too small to provide drought relief when Kremasta is depleted, and simply release whatever discharges arrive from upstream. The power generation sequence (Figure 4.9) follows the pattern of the release sequence. Total power generation fluctuates around 190 GWH per month, except during floods when higher releases are necessary to avoid violation of the storage constraints or during droughts when the system is seriously depleted. Average system energy generation is 2096 GWH, of which 1021 GWH are generated by

Kremasta, 713 GWH are generated by Kastraki, and 362 GWH are generated by Stratos.

Figures 4.10, 4.11, and 4.12 summarize the results of the 600 x 10^6 m^3 diversion scenario. The reservoir elevation sequences (Figure 4.10) exhibit the same seasonal fluctuation pattern and flood and drought occurrences as the no diversion case. However, the release and energy figures (4.11 and 4.12) indicate a more significant change. There are now more months in which the system is unable to meet its downstream water supply requirements, and the total monthly energy generation fluctuates around 140 GWH. On the average, annual energy generation has dropped to 1789 GWH, of which 874 GWH are generated by Kremasta, 606 GWH are generated by Kastraki, and 309 GWH are generated by Stratos. Thus, on an annual basis, the diversion scenario results in a 15% decrease in average energy generation.

To understand the seasonal effect of the diversion on water supply and energy generation, we developed monthly frequency curves. These curves are plotted for Stratos discharges on Figures 4.13 through 4.24, and for the system energy generation on Figures 4.25 through 4.36. (The numerical values of each curve can be found in Appendix B.) The figures show the frequency of exceedance corresponding to the zero and the 600 x 10^6 m^3 diversion scenarios, estimated using 44 values for each month. (Frequency of exceedance is the probability that, in a given month, the discharge or energy generation will exceed a particular value.) For comparison, the discharge frequency curves also include the required minimum downstream discharge level.

The main feature of all frequency curves is that, for a particular value of the discharge or energy generation, the frequency of exceedance for the diversion scenario is lower than that for the base case. This decrease varies with the month and across the range of the discharge or energy generation. For example, in July, the discharge plot (Figure 4.19) indicates that the probability that Stratos discharge will exceed 350 million cubic meters is about 70% in the base case, while it is practically zero in the diversion scenario. On the other hand, the probability that the discharge will meet the downstream water supply requirement (147 million cubic meters) in the same month is 96% for the base case and 94% under the diversion. For the present downstream demand conditions, the latter comparison is more important and shows that in July the effect of the diversion is not very significant. The same comparison for all months of the year is depicted on the following table.

Table 4.1: Water Supply Reliability Comparison

Month	Water Supply (10^6 m^3)	Base Case Reliability (%)	Diversion Reliability (%)
January	55.2	100	100
February	55.2	100	100
March	55.2	100	100
April	55.2	100	100
May	147	95	97
June	147	96	96
July	147	96	94
August	147	97	92
September	147	93	91
October	55.2	98	93
November	55.2	100	94
December	55.2	100	100

The comparison shows that the reliability reduction is fairly small, ranging from 0 to 6%. However, it is *emphatically* noted that these results are valid for the *present* water demand conditions. If, as a result of agricultural development, the irrigation requirements increase, the reliability of meeting the increased demand will be significantly less. This is clearly shown on Figures 4.13 to 4.24.

Figures 4.25 through 4.36 show the effect of the diversion in energy generation. Although, the average annual energy generation reduction was estimated earlier to be about 15%, the frequency curves show that the monthly generation reductions can be larger. For example, in June, the energy amounts that are exceeded 50% of the time (median) are 190 GWH in the base case and 153 GWH under the diversion, indicating a 20% reduction in the most likely generation amount for this month. At the 75% and 25% frequency of exceedance levels, the generation reduction due to the diversion is respectively about 11% and 15%. This comparison for all months of the year is summarized in Table 4.2.

Table 4.2: Comparison of Monthly Energy Generation Reliability - Units in GWH/Month

Month	25% Reliability Level		50% Reliability Level		75% Reliability Level	
	Base Case	Diversion	Base Case	Diversion	Base Case	Diversion
January	195	177	189	141	150	123
February	193	162	189	141	149	126
March	191	158	189	141	151	136
April	193	166	190	147	155	135
May	194	166	190	155	154	140
June	196	167	190	153	156	140
July	201	170	190	153	152	139
August	202	175	190	158	146	121
September	201	176	190	158	145	121
October	201	178	190	158	154	126
November	203	178	187	162	145	112
December	195	177	188	141	151	123

The table shows that the most likely energy generation reduction (at the 50% exceedance level) is about 40 to 50 GWH per month, representing a 22 to 26% decrease over the base case. This is a significant consequence, with a concomitant economic loss. However, the economic value of the energy loss cannot be addressed by the models developed herein. For this, one would have to develop daily and hourly control models and investigate the availability of hydropower in relation to the power generation cost of the thermal system. This and other possible extensions of this research are briefly discussed in the following chapter.

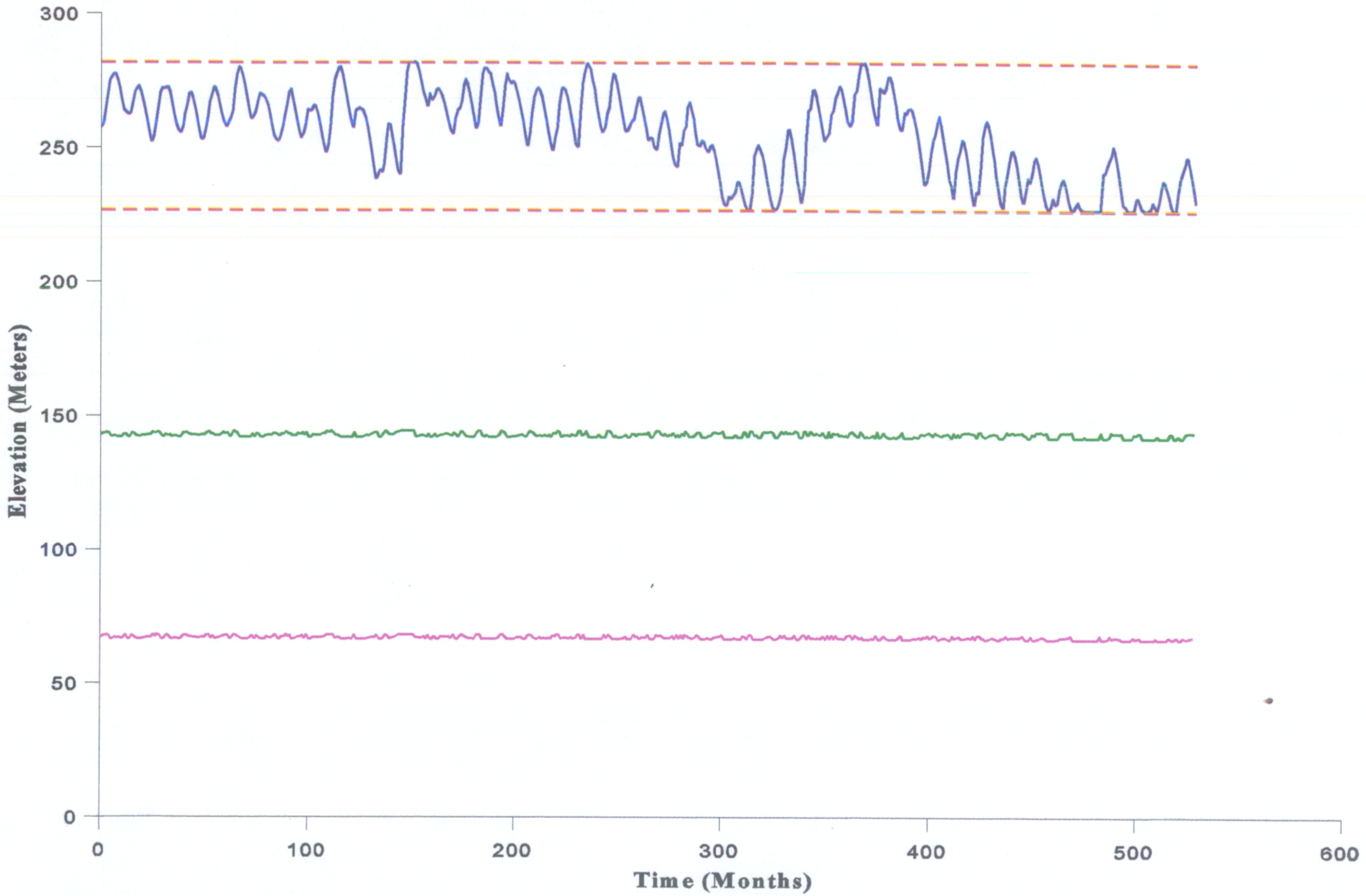

Figure 4.7: Elevation Sequences; 95% Reliability; Diversion=0 Million Cubic Meters/Year

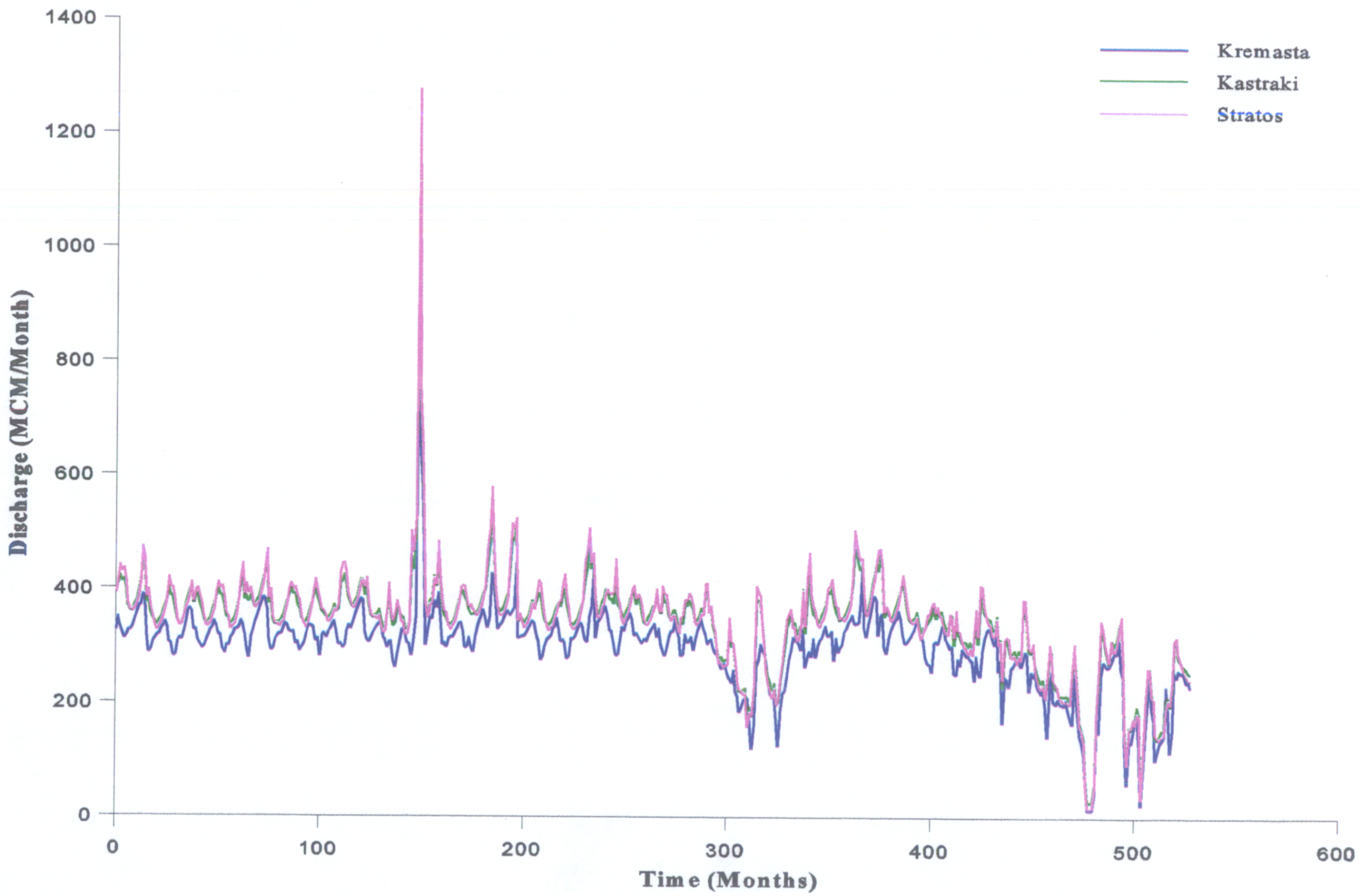

Figure 4.8 : Discharge Sequence with Diversion = 0 MCM/Year

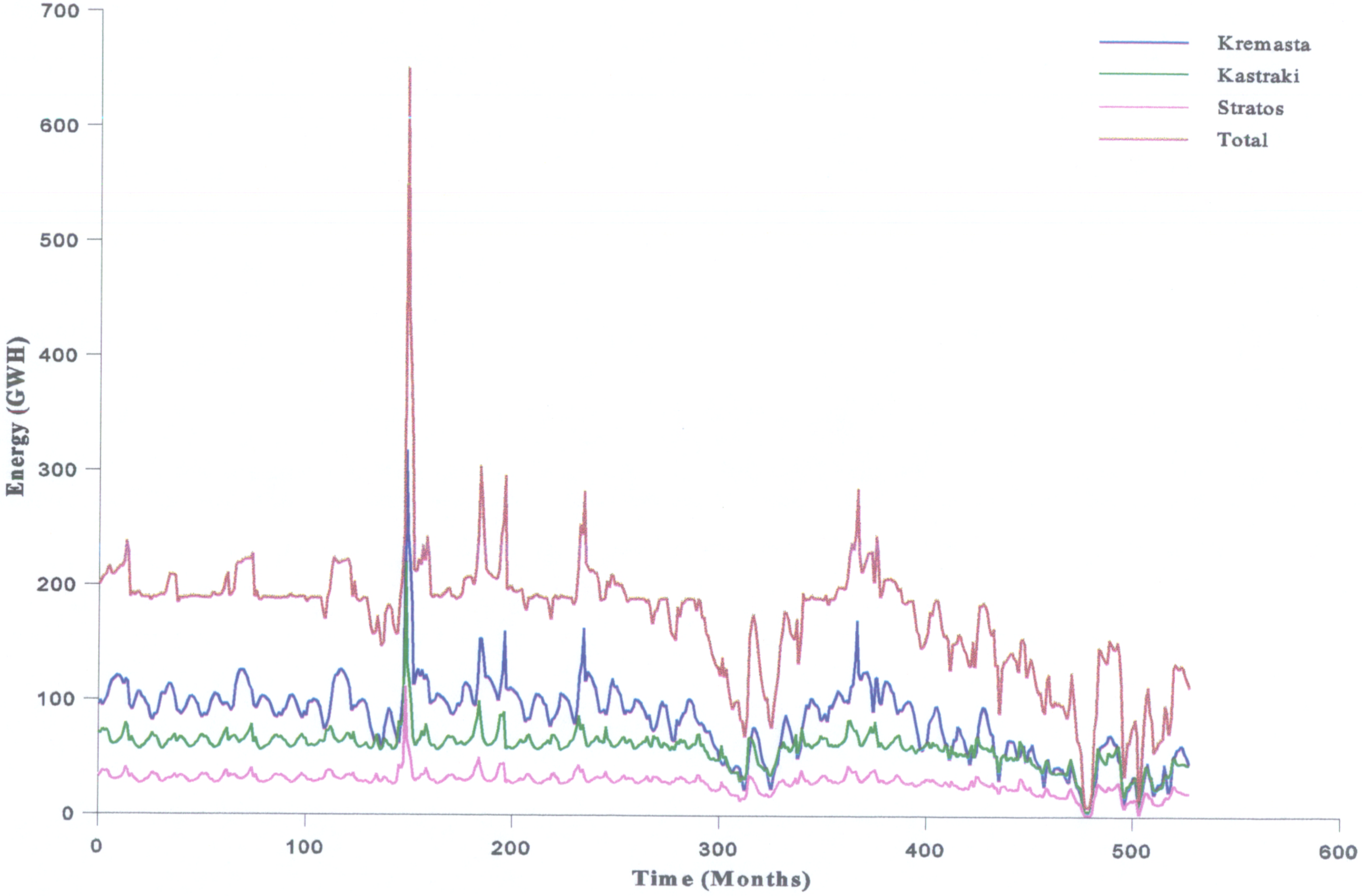

Figure 4.9: Energy Generation Sequence with Diversion = 0 MCM/Year

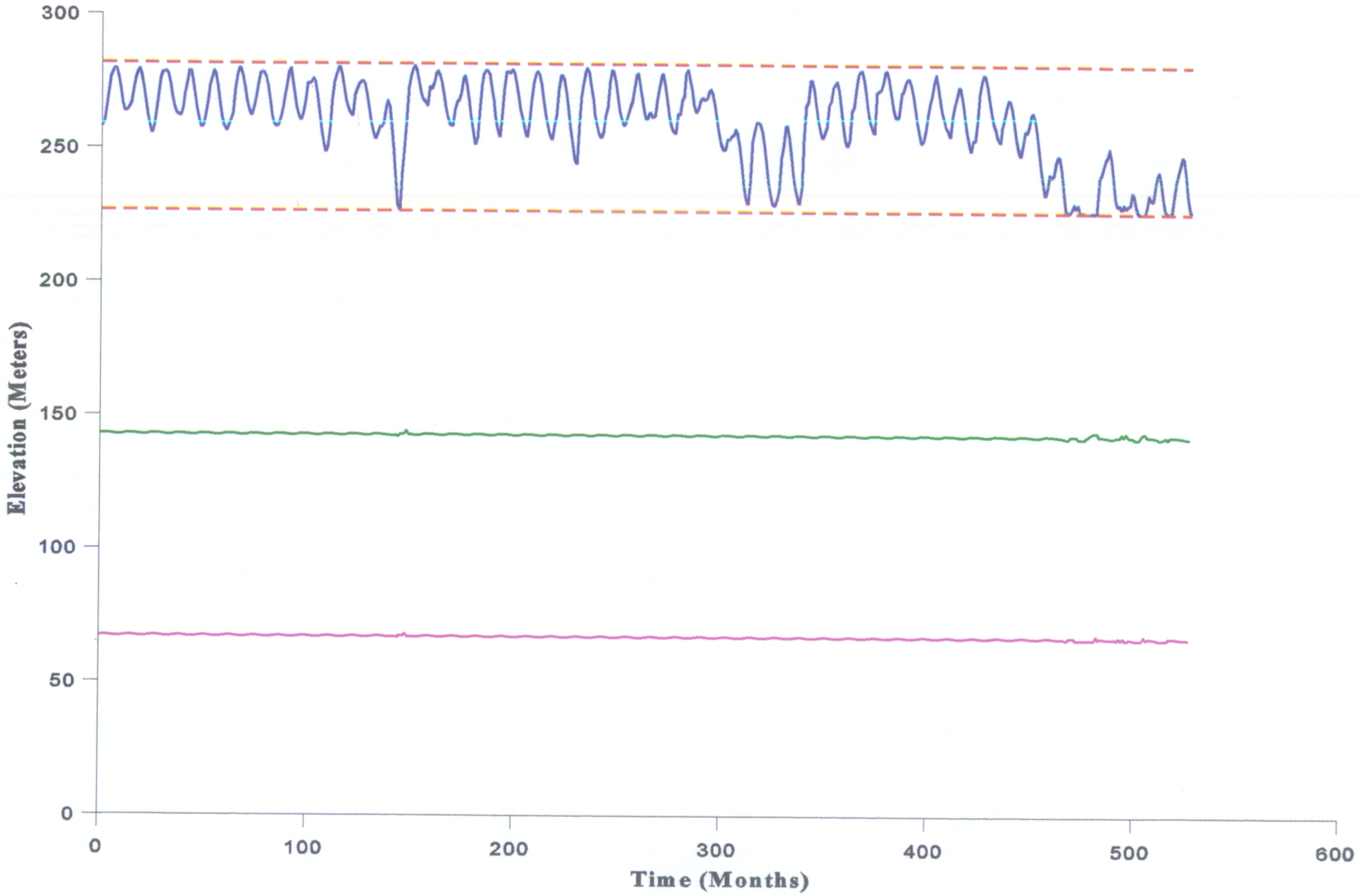

Figure 4.10: Elevation Sequences; 95% Reliability; Diversion= 600 Million Cubic Meters/Year

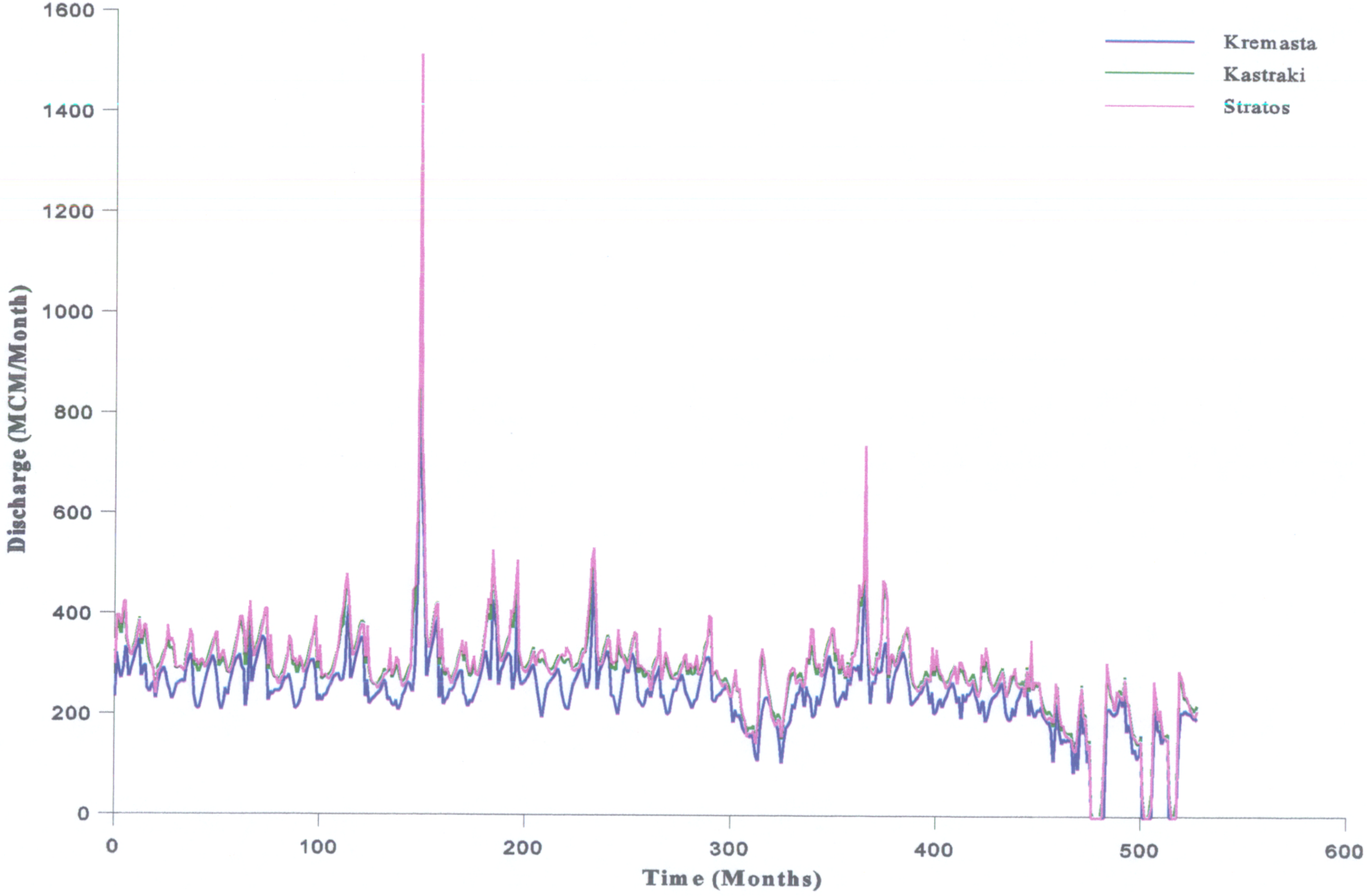

Figure 4.11: Discharge Sequence with Diversion = 600 MCM/Year

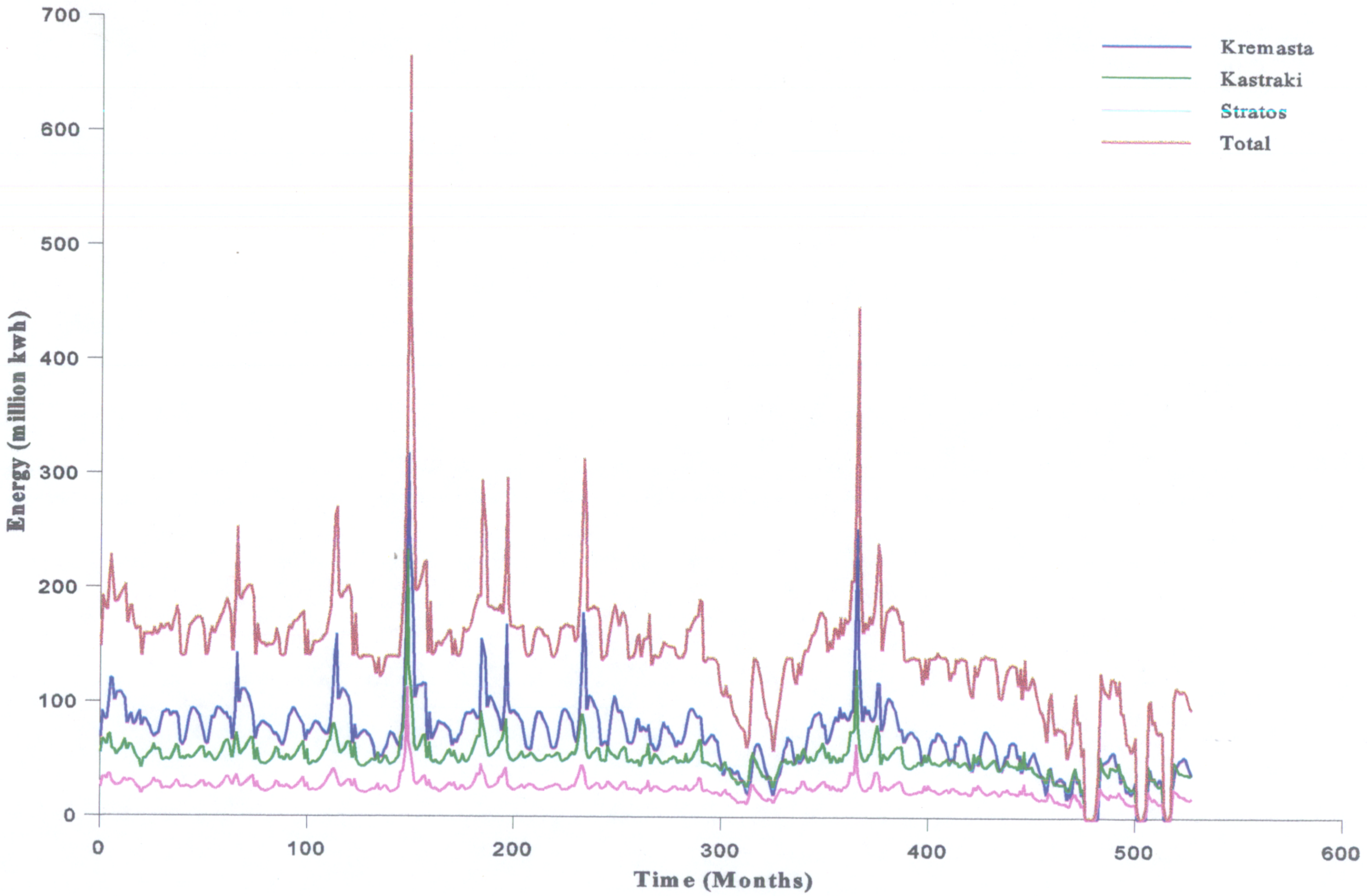

Figure 4.12: Energy Generation Sequence with Diversion = 600 MCM/Year

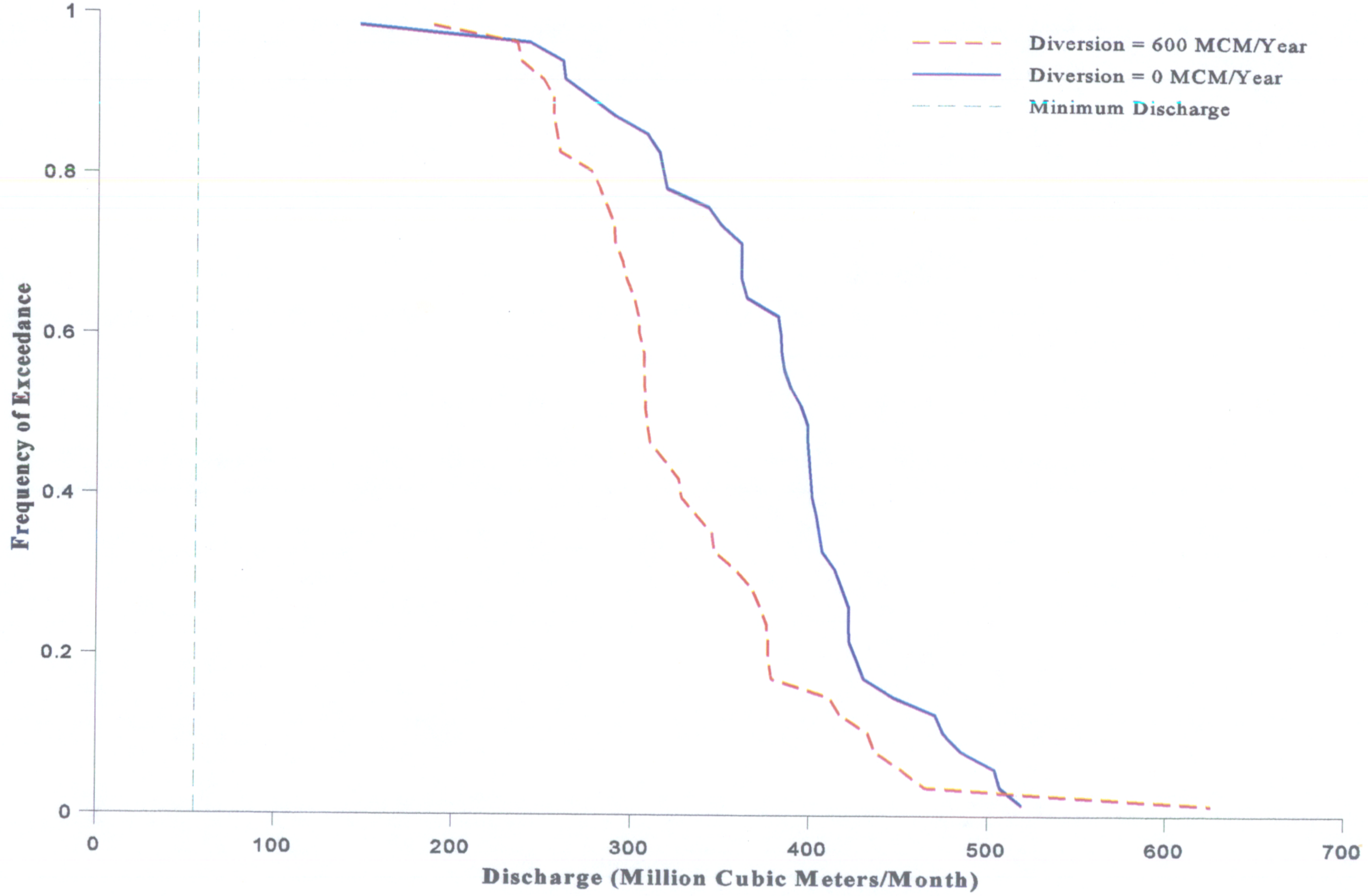

Figure 4.13: Discharge Frequency of Exceedance; January

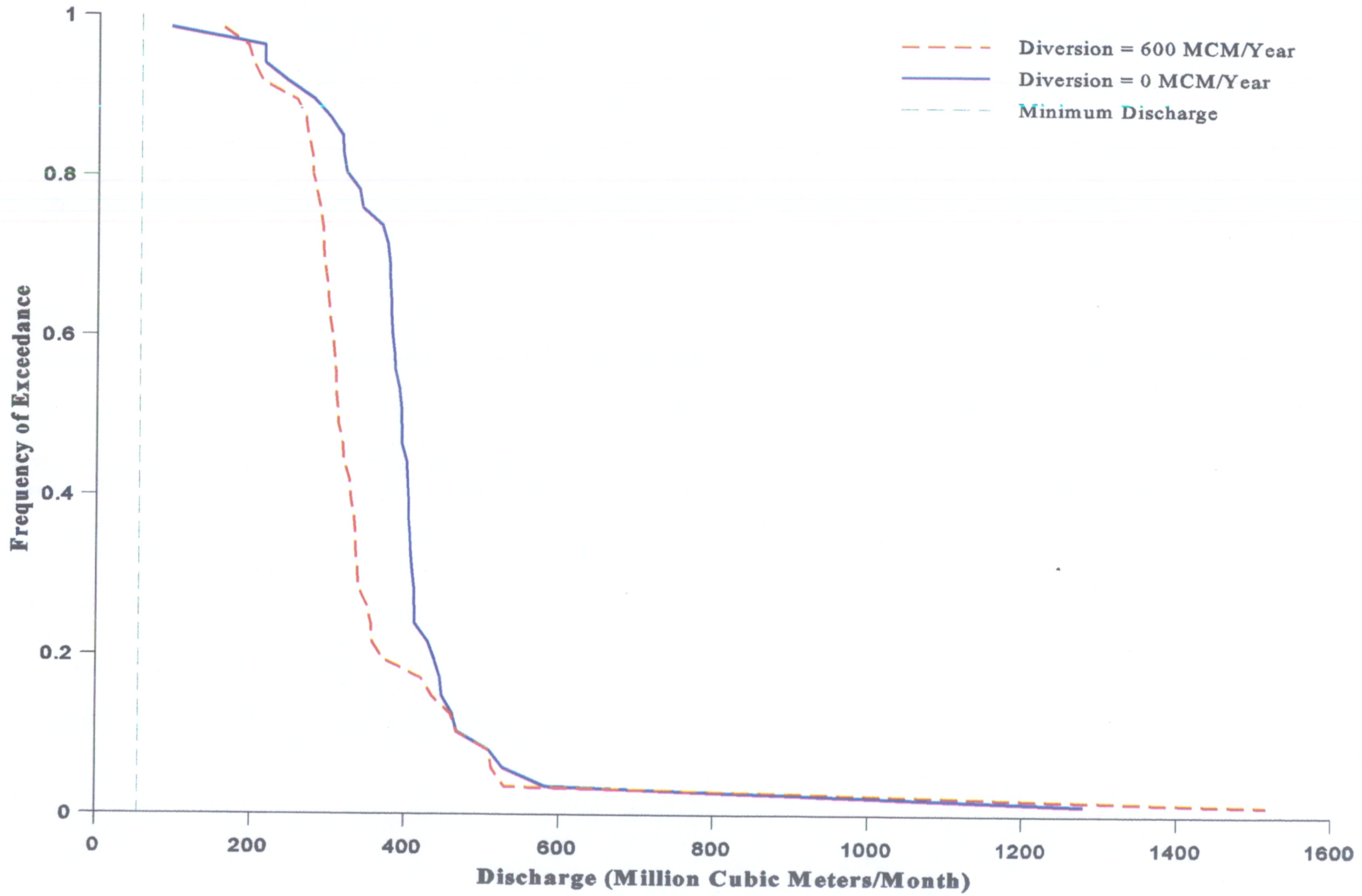

Figure 4.14: Discharge Frequency of Exceedance; February

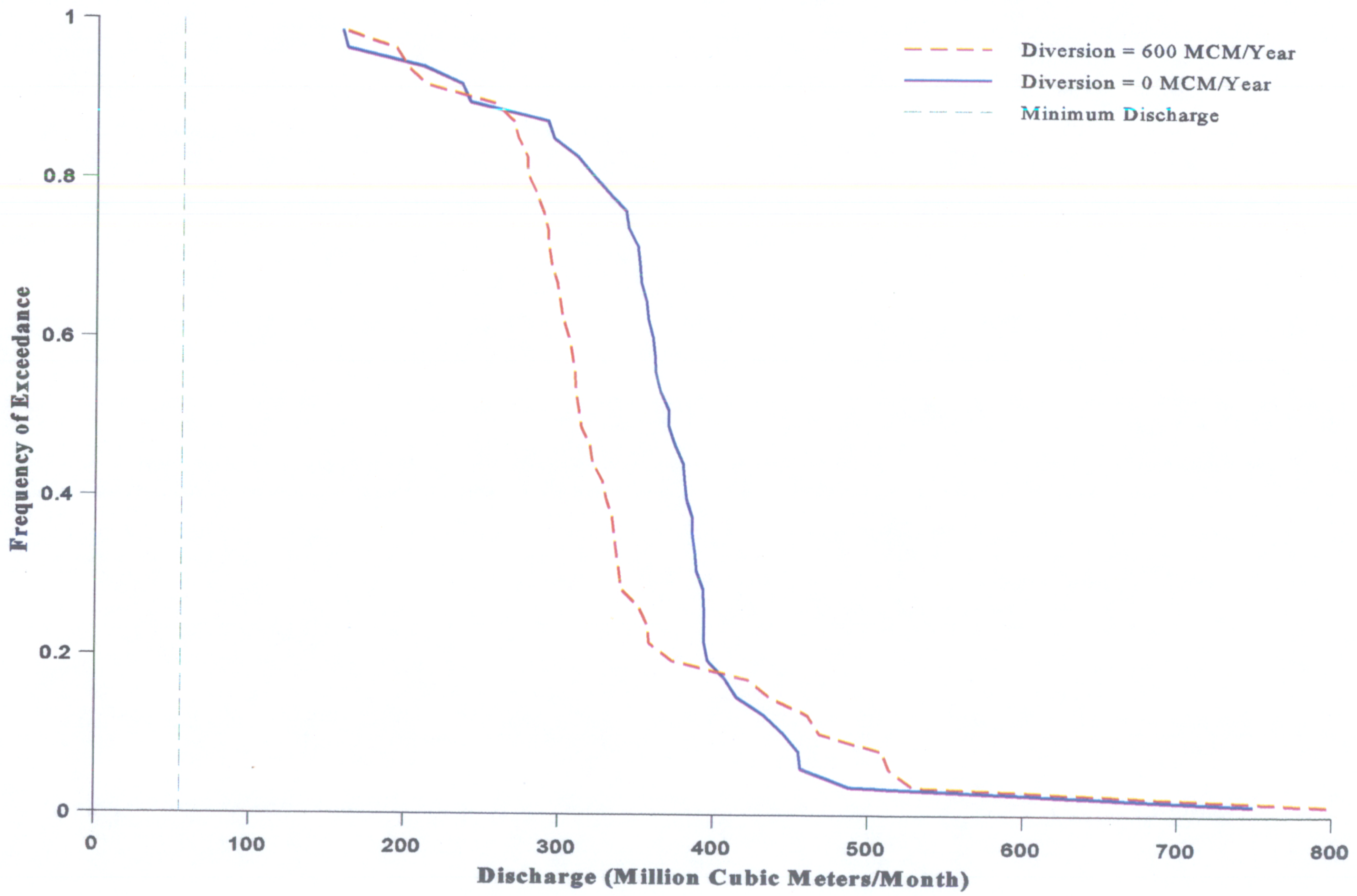

Figure 4.15: Discharge Frequency of Exceedance; March

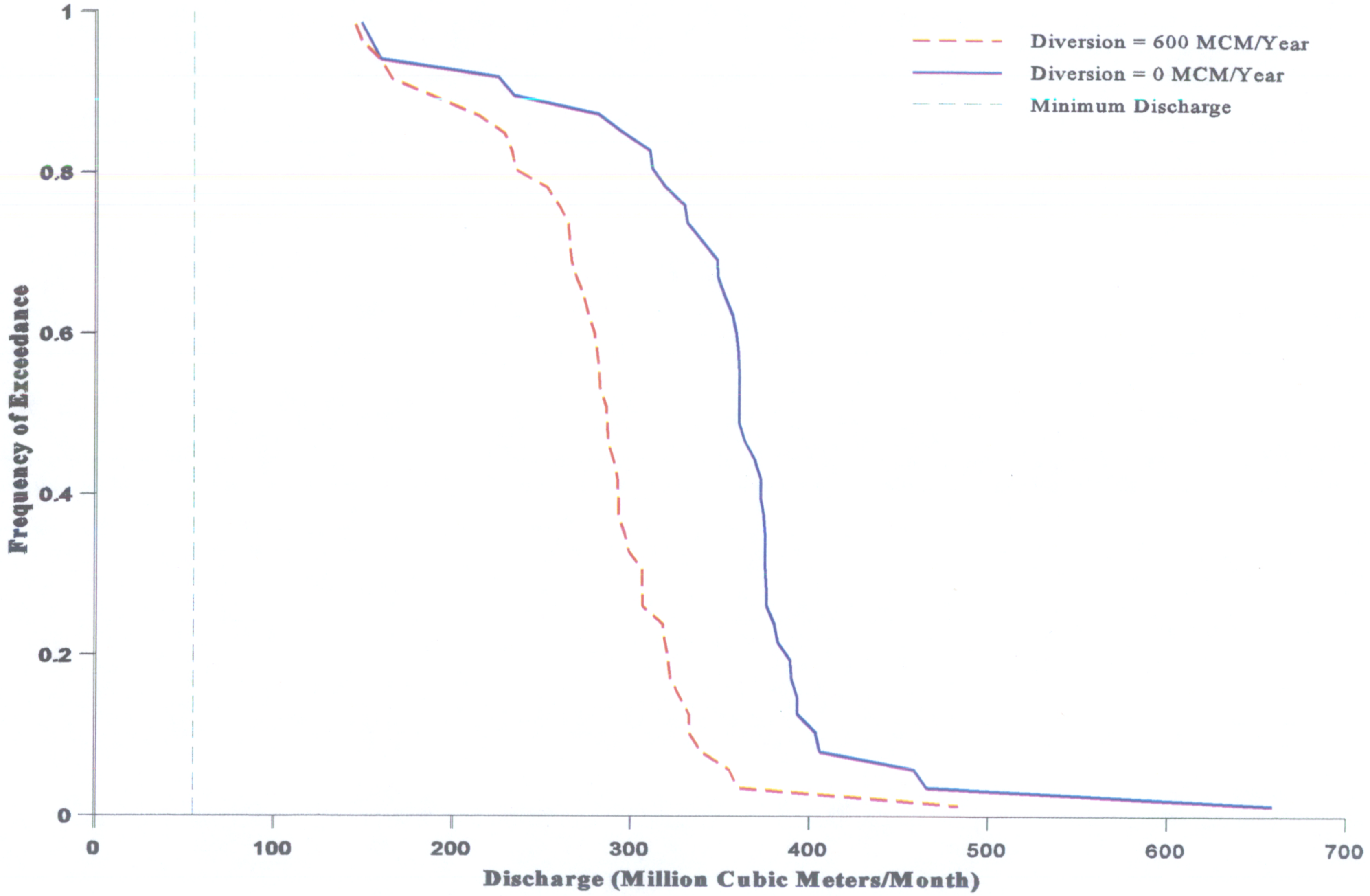

Figure 4.16: Discharge Frequency of Exceedance; April

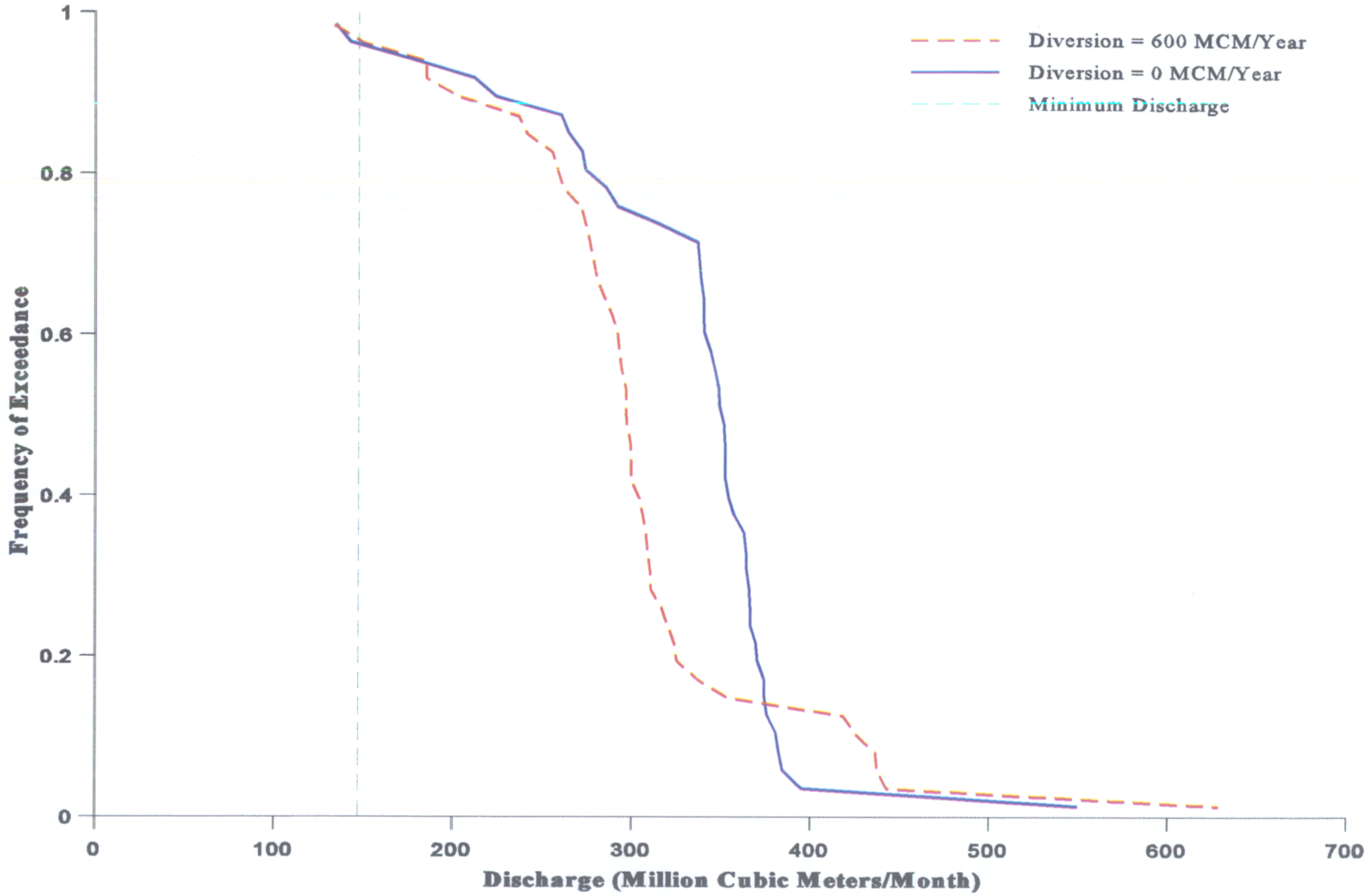

Figure 4.17: Discharge Frequency of Exceedance; May

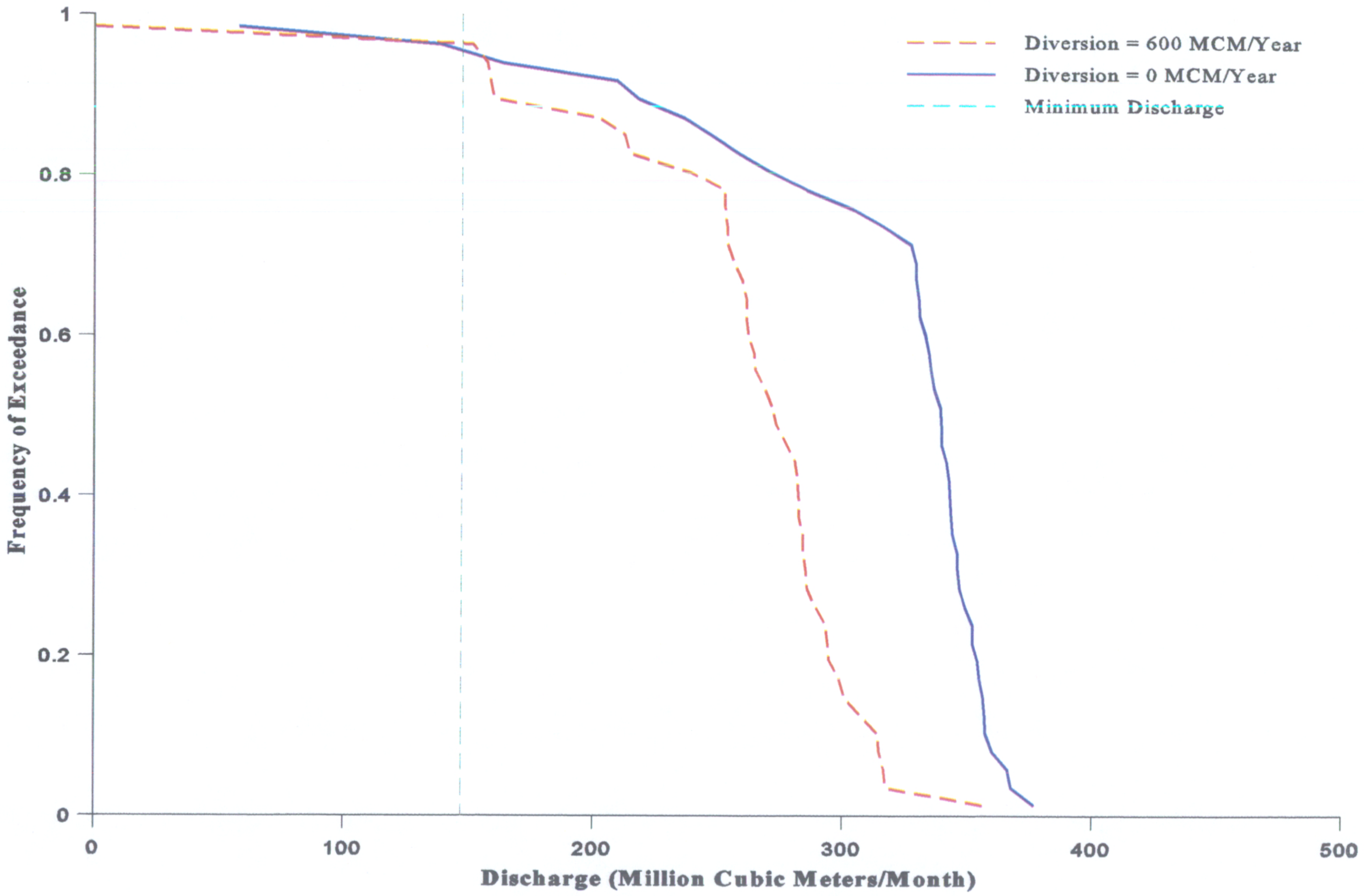

Figure 4.18: Discharge Frequency of Exceedance; June

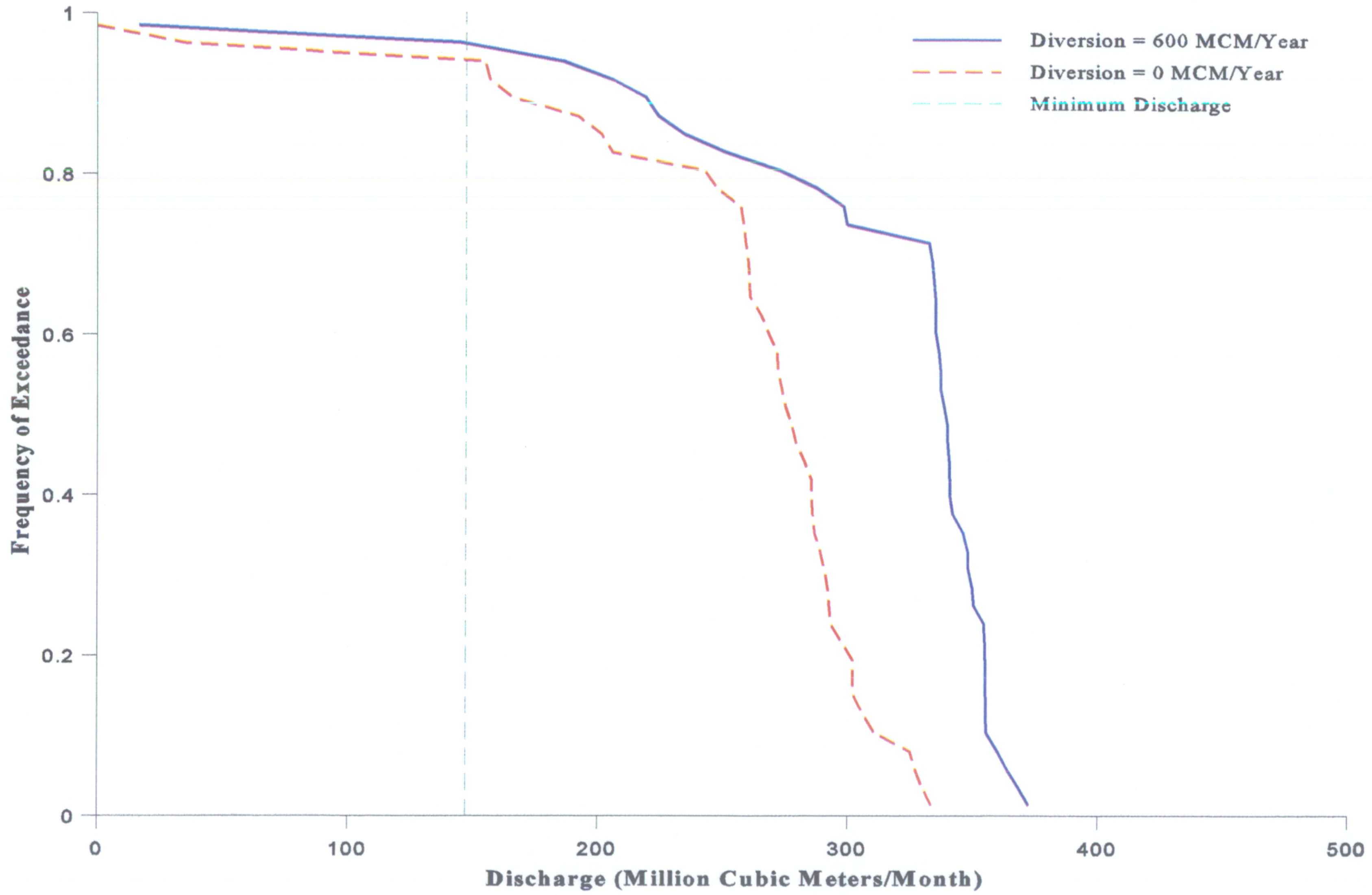

Figure 4.19: Discharge Frequency of Exceedance; July

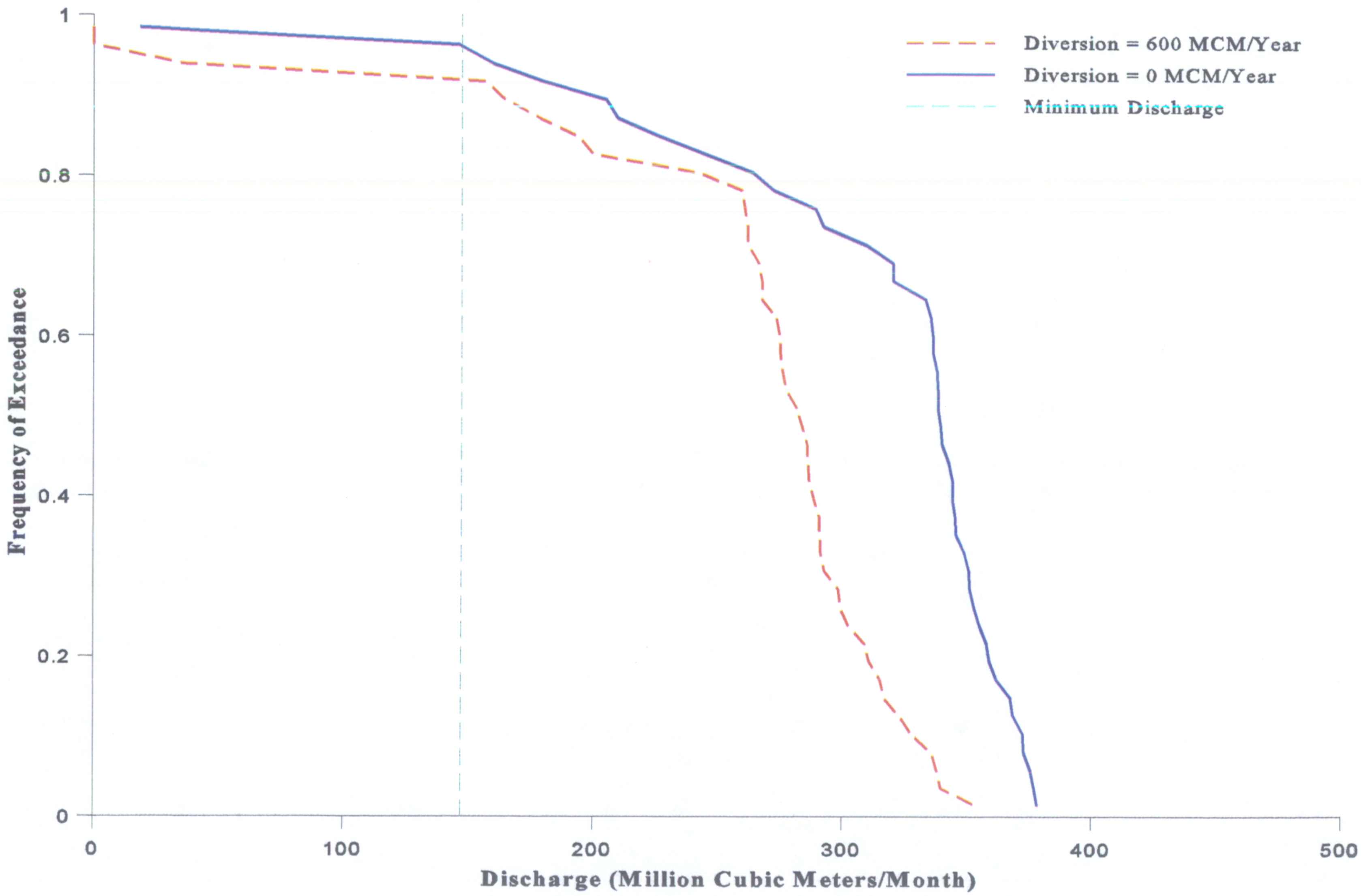

Figure 4.20: Discharge Frequency of Exceedance; August

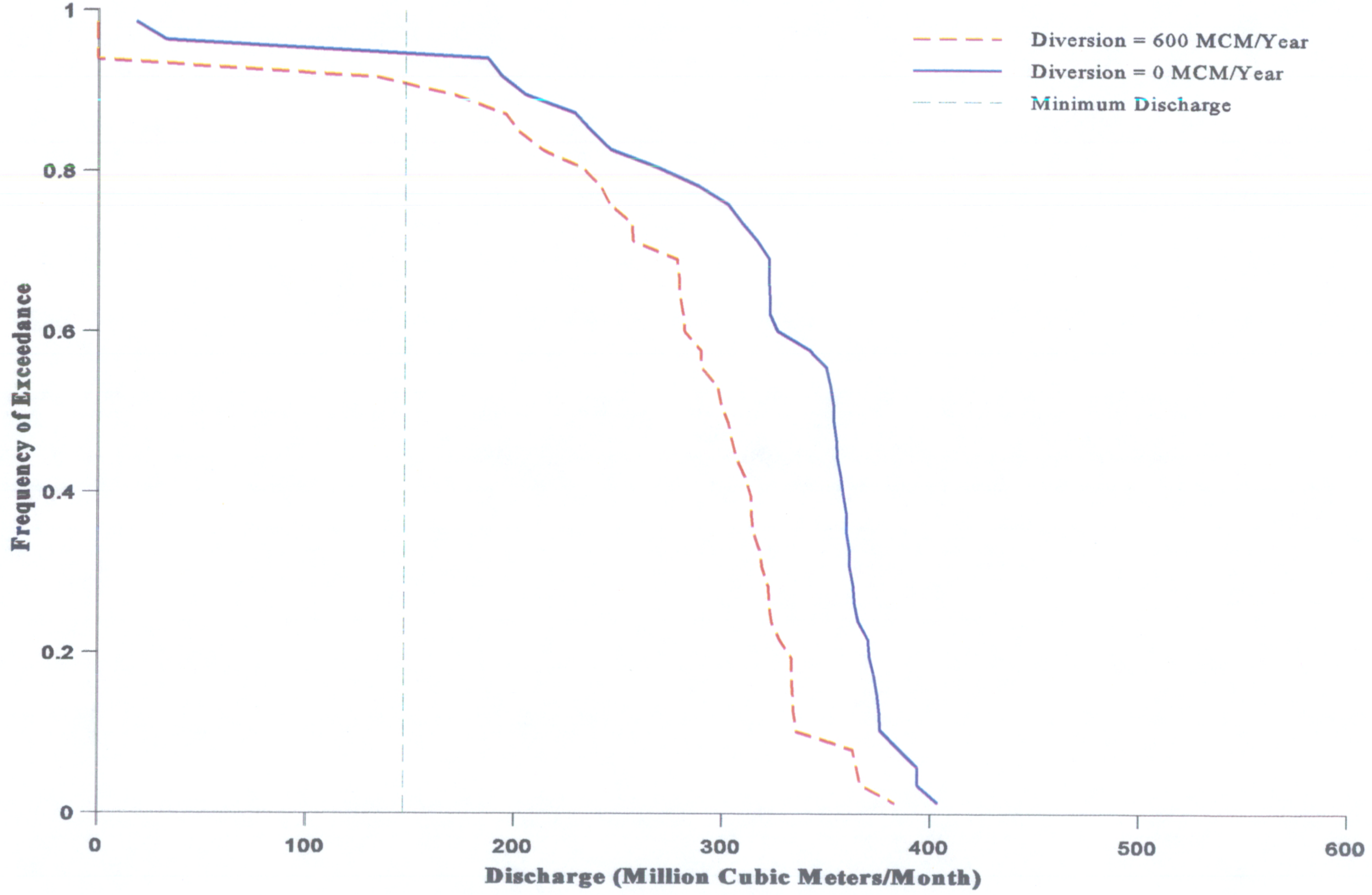

Figure 4.21: Discharge Frequency of Exceedance; September

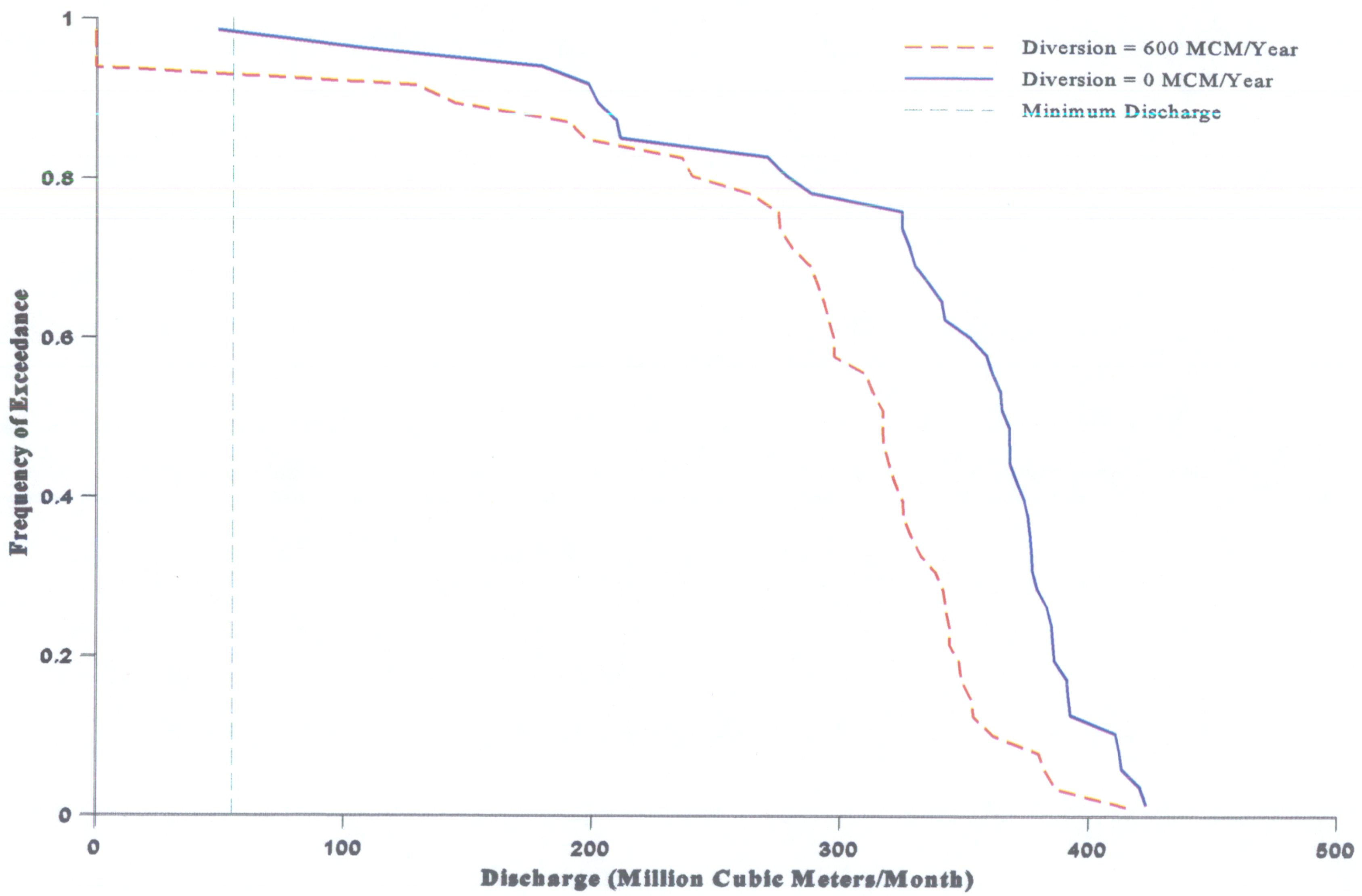

Figure 4.22: Discharge Frequency of Exceedance; October

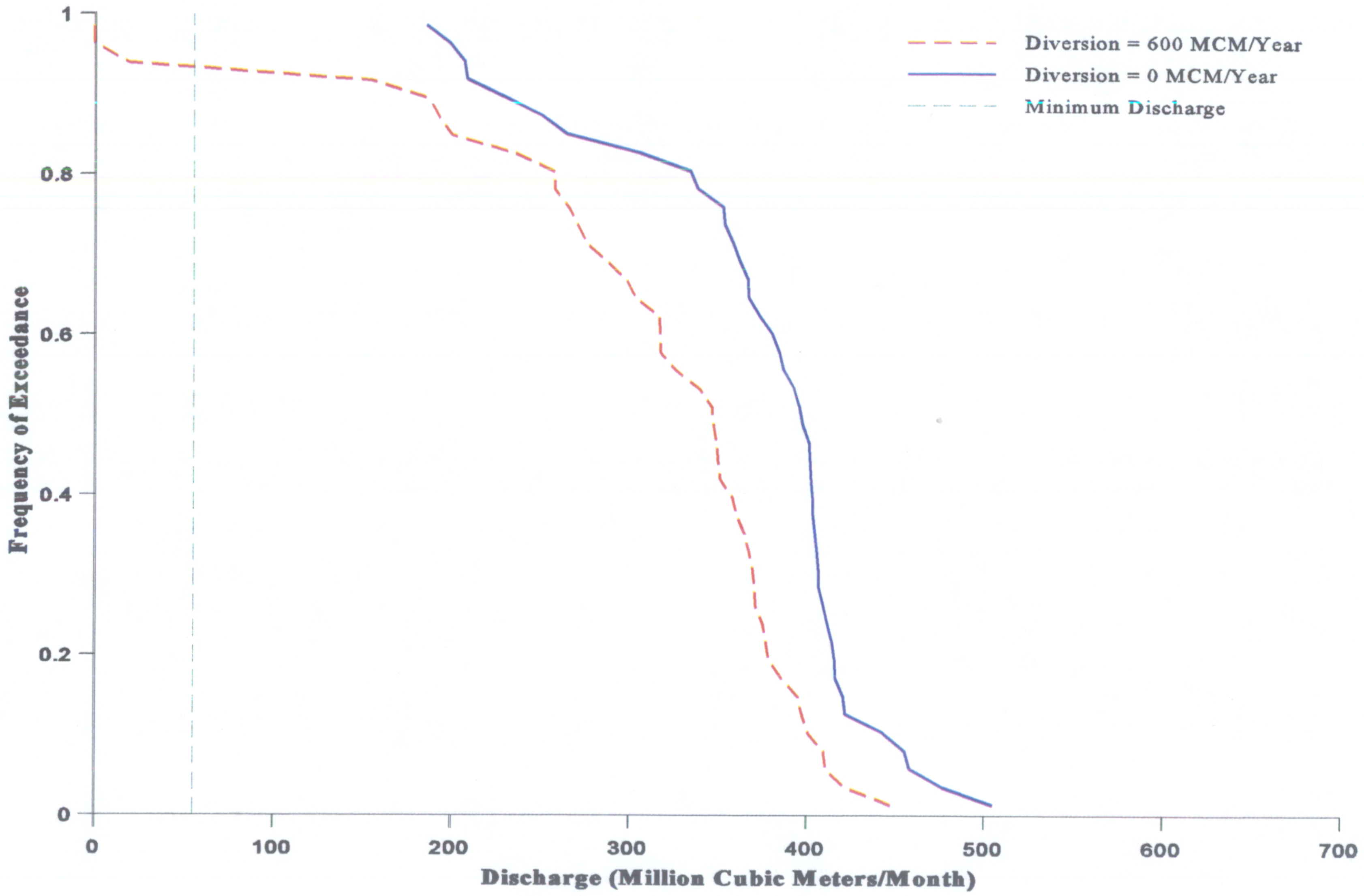

Figure 4.23: Discharge Frequency of Exceedance; November

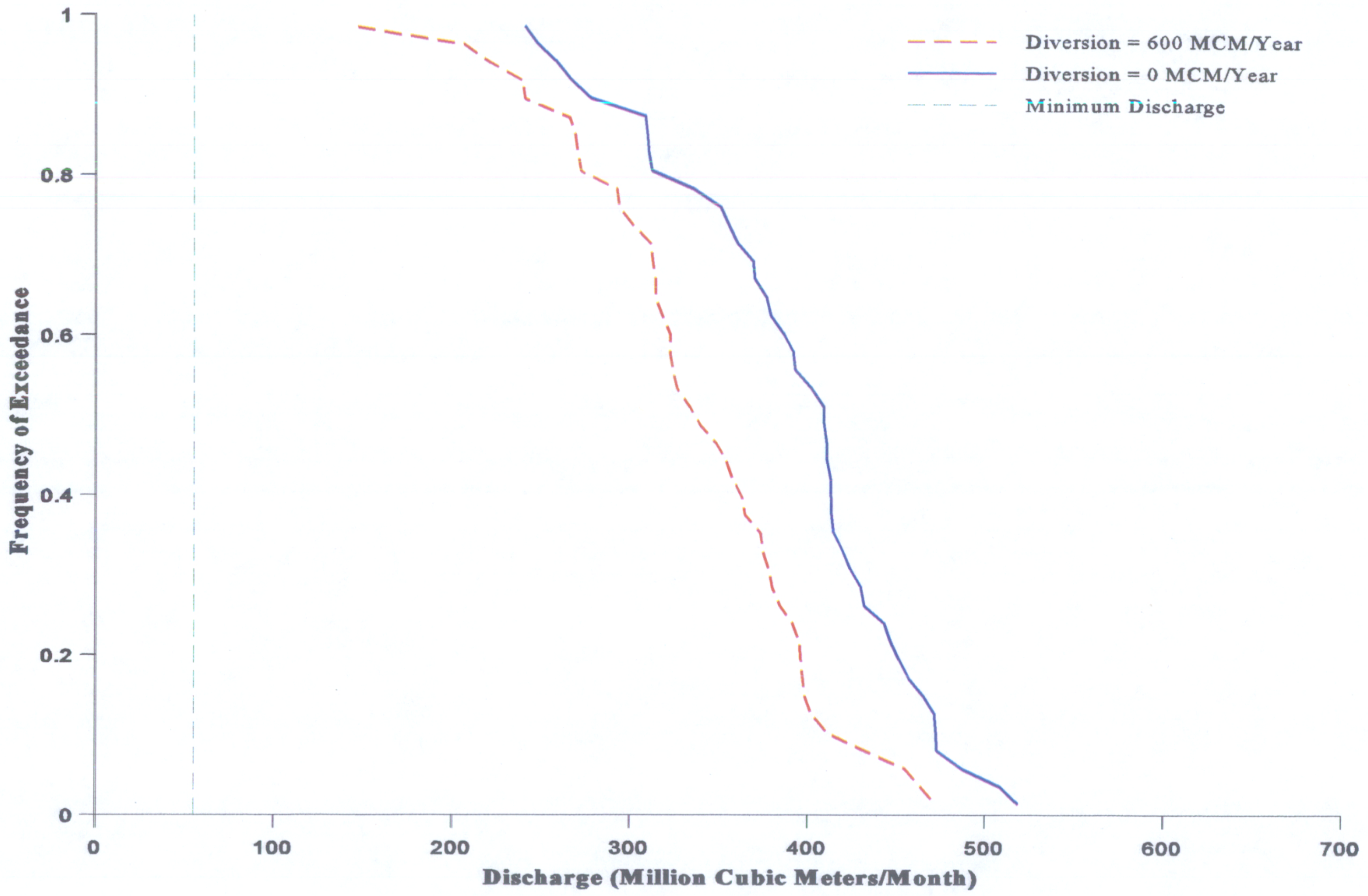

Figure 4.24: Discharge Frequency of Exceedance; December

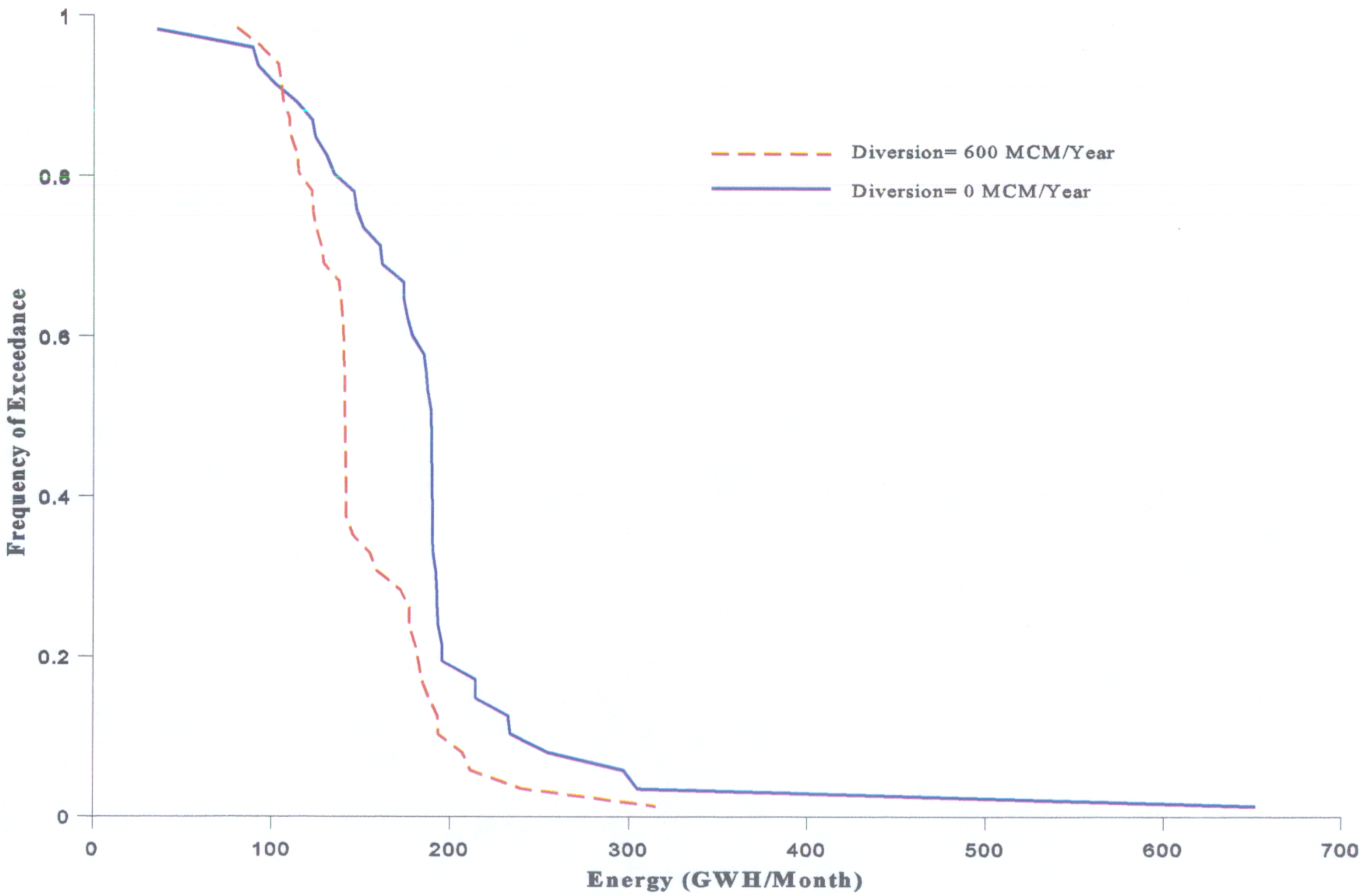

Figure 4.25: Energy Frequency of Exceedance; January

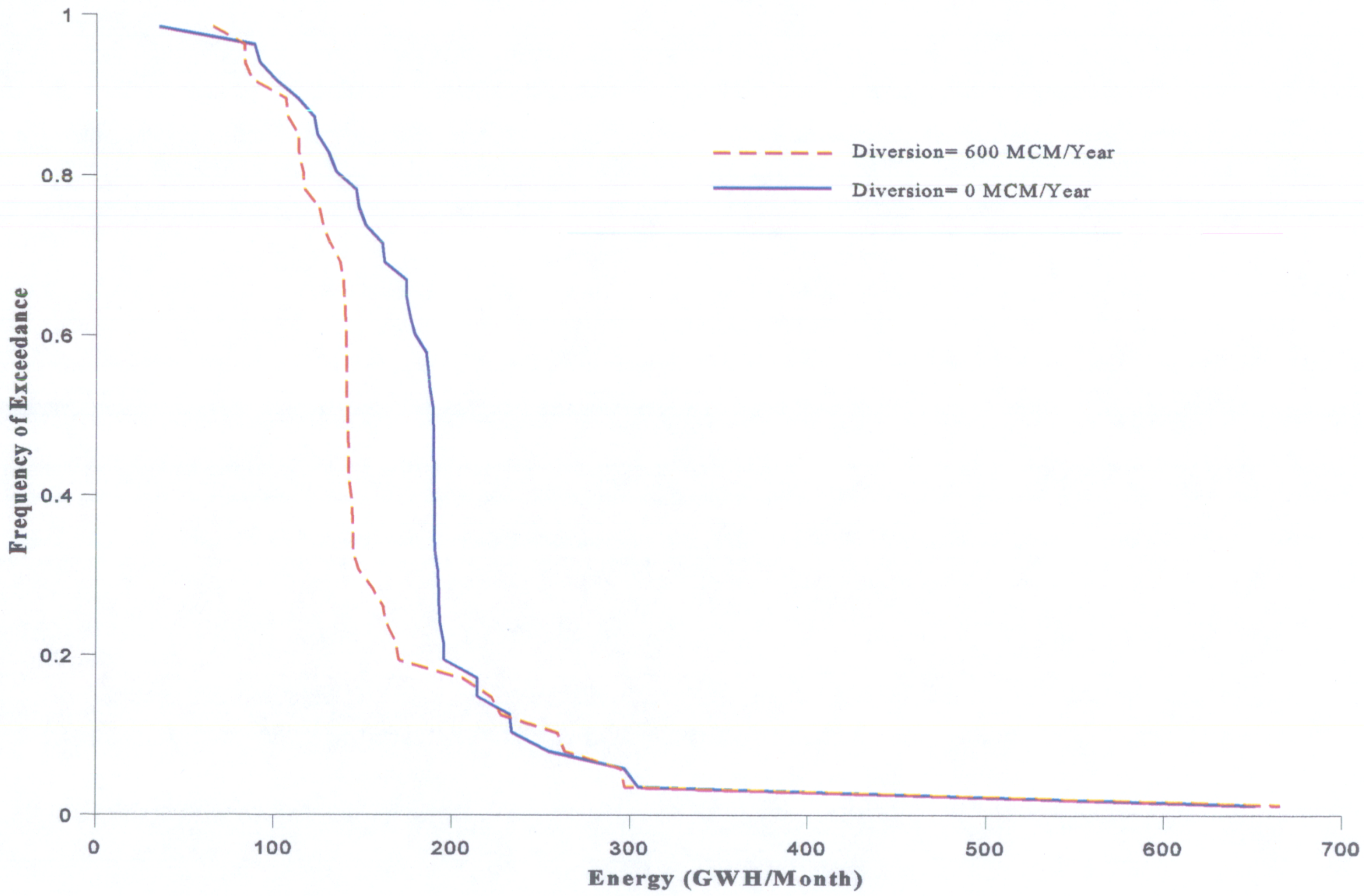

Figure 4.26: Energy Frequency of Exceedance; February

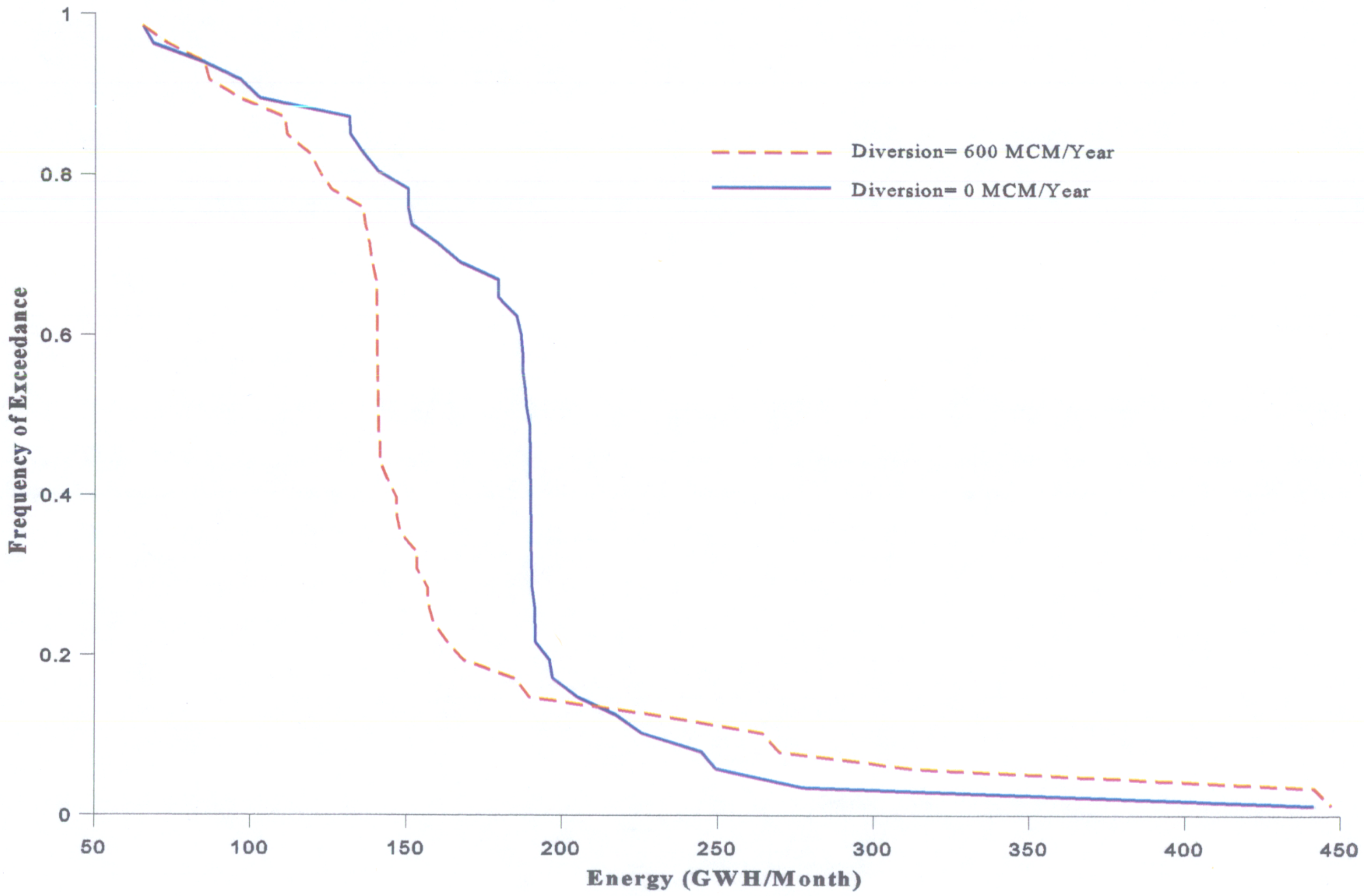

Figure 4.27: Energy Frequency of Exceedance; March

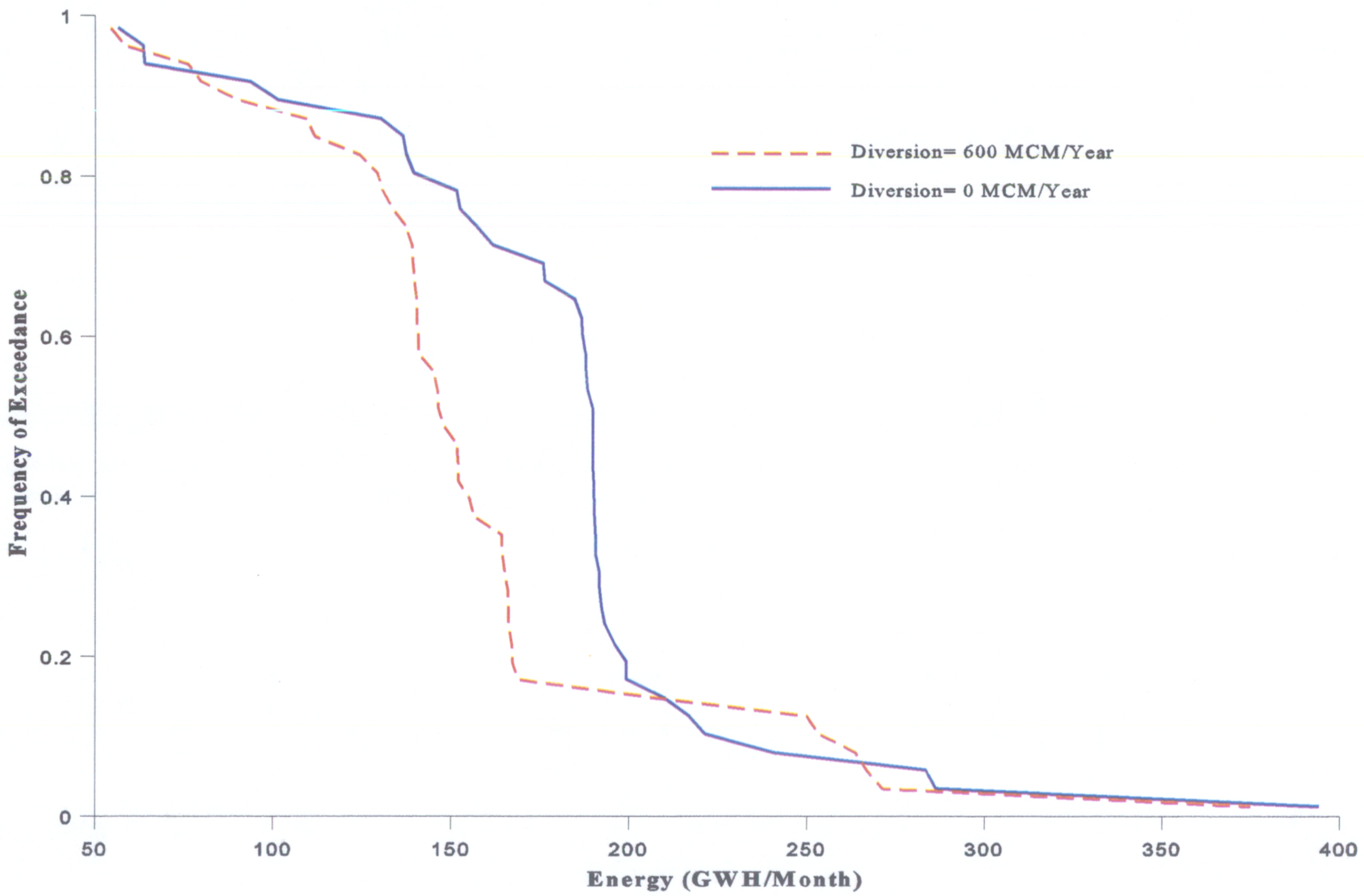

Figure 4.28: Energy Frequency of Exceedance; April

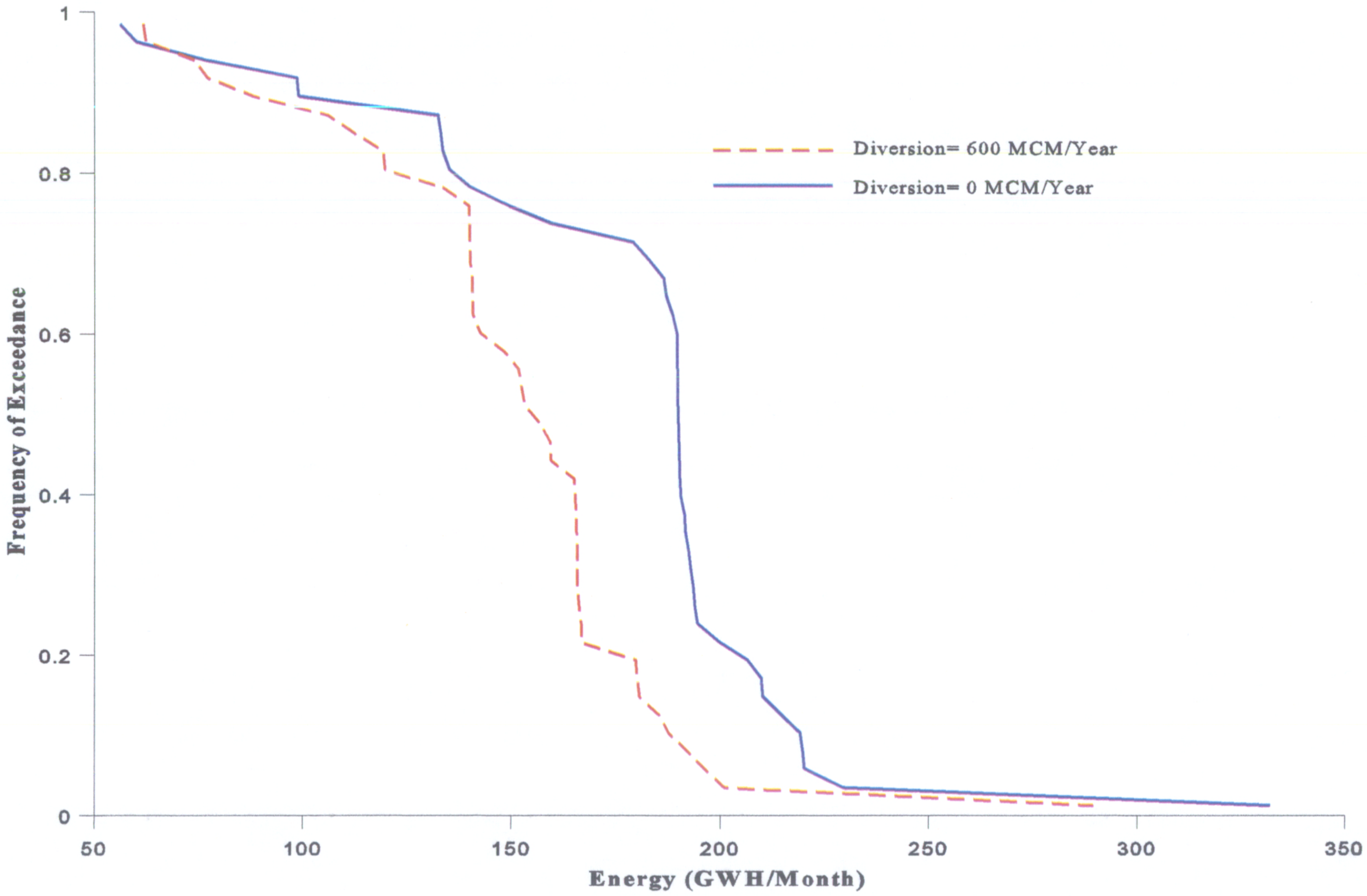

Figure 4.29: Energy Frequency of Exceedance; May

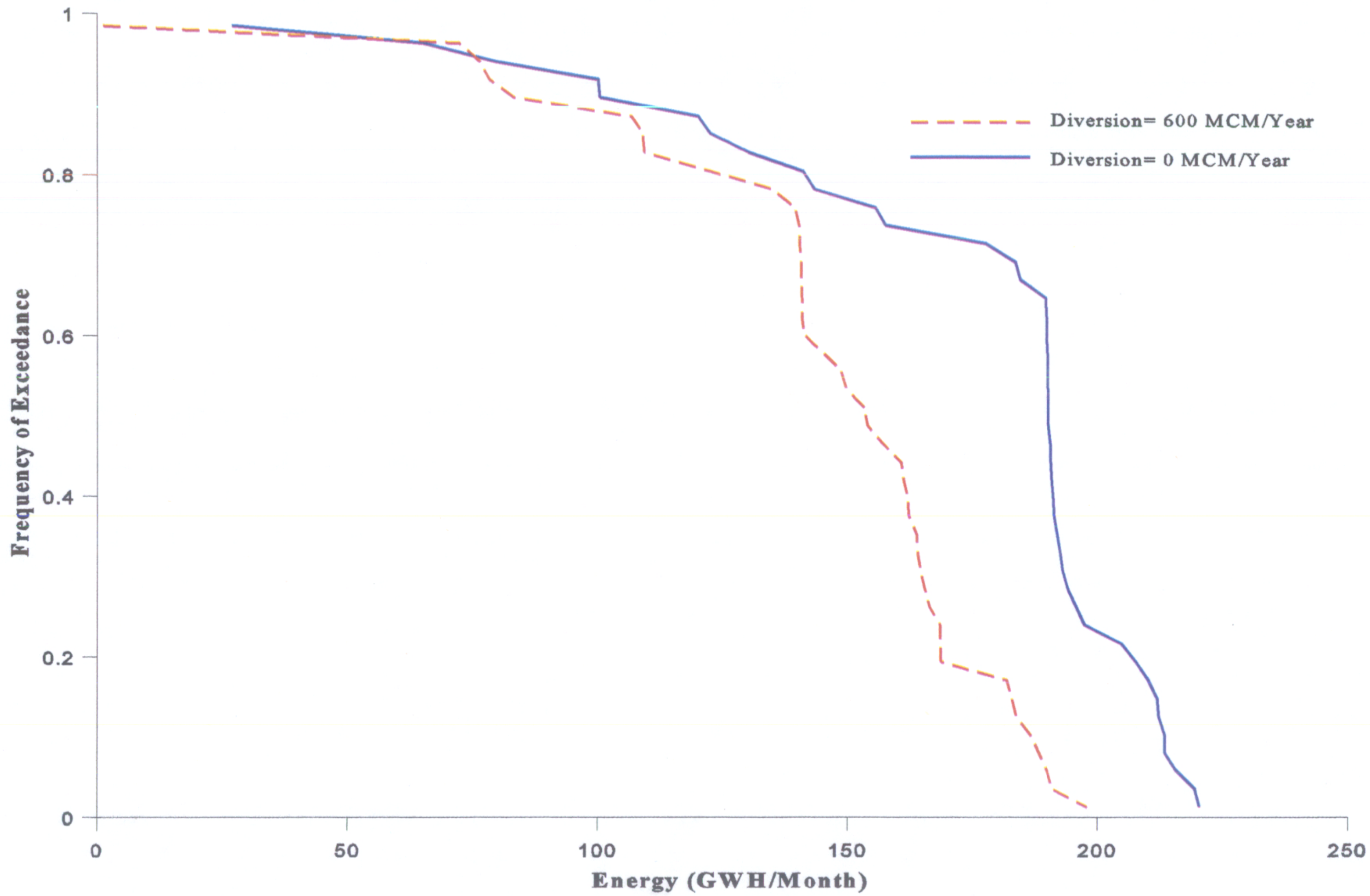

Figure 4.30: Energy Frequency of Exceedance; June

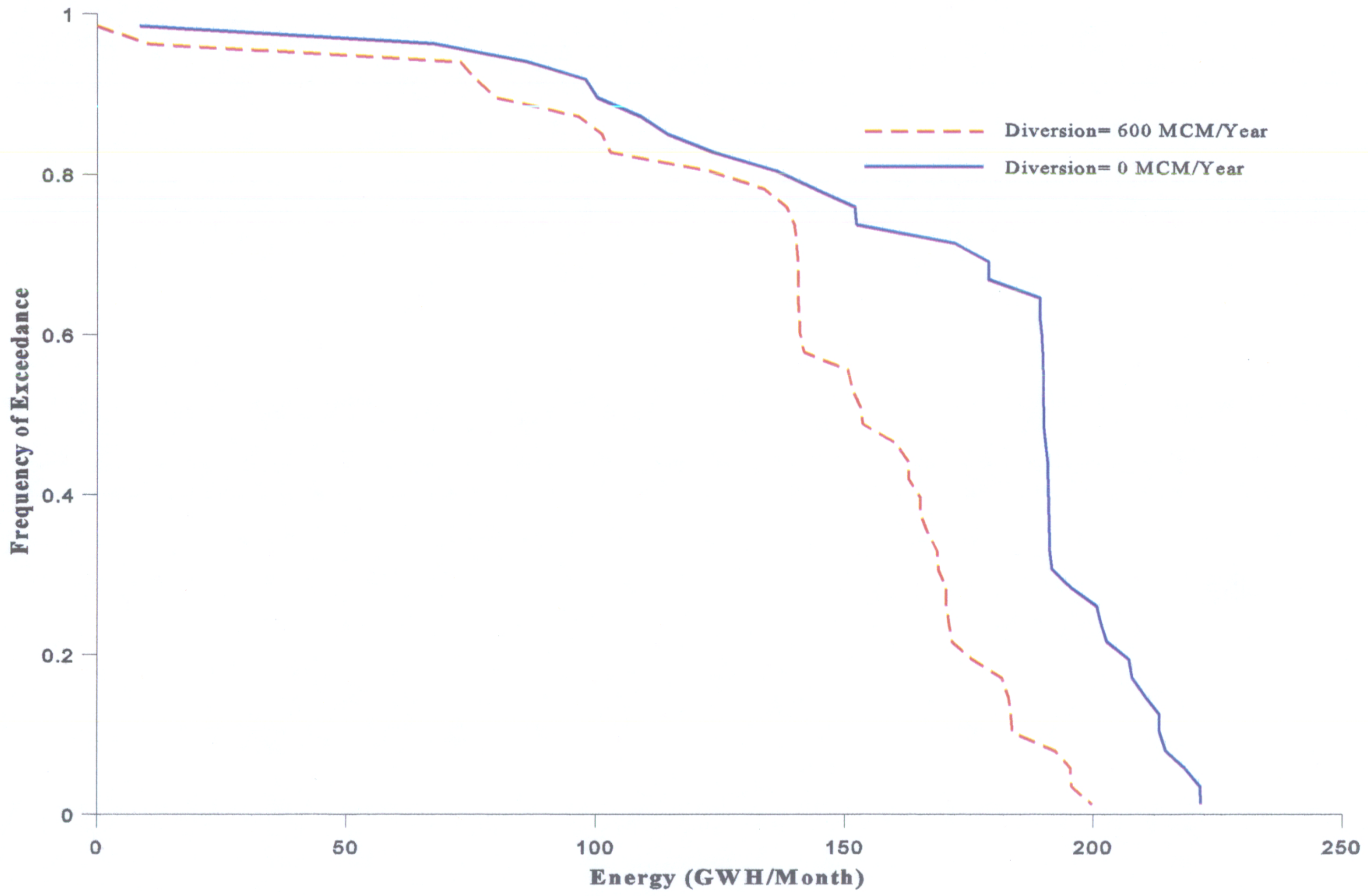

Figure 4.31: Energy Frequency of Exceedance; July

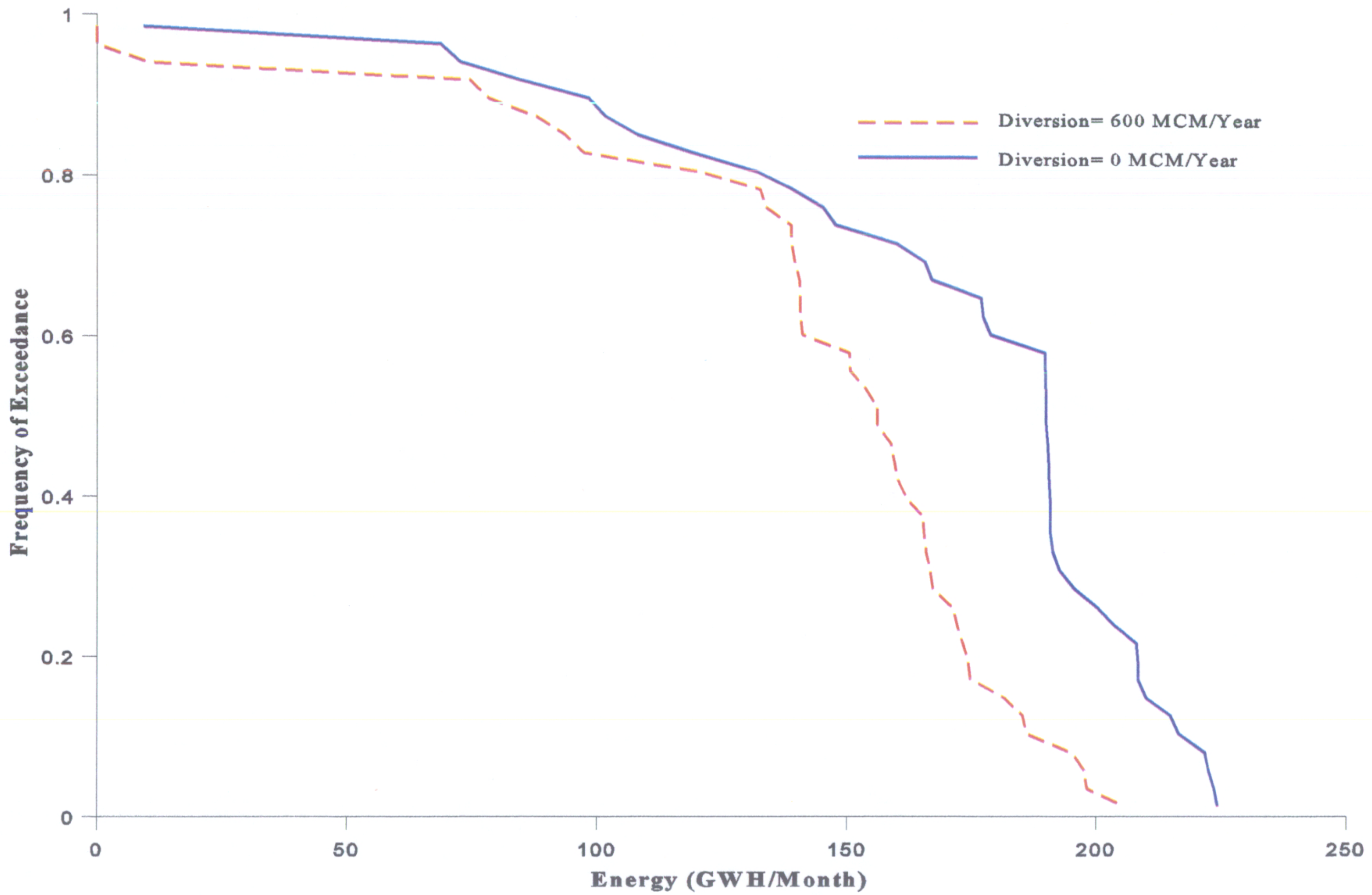

Figure 4.32: Energy Frequency of Exceedance; August

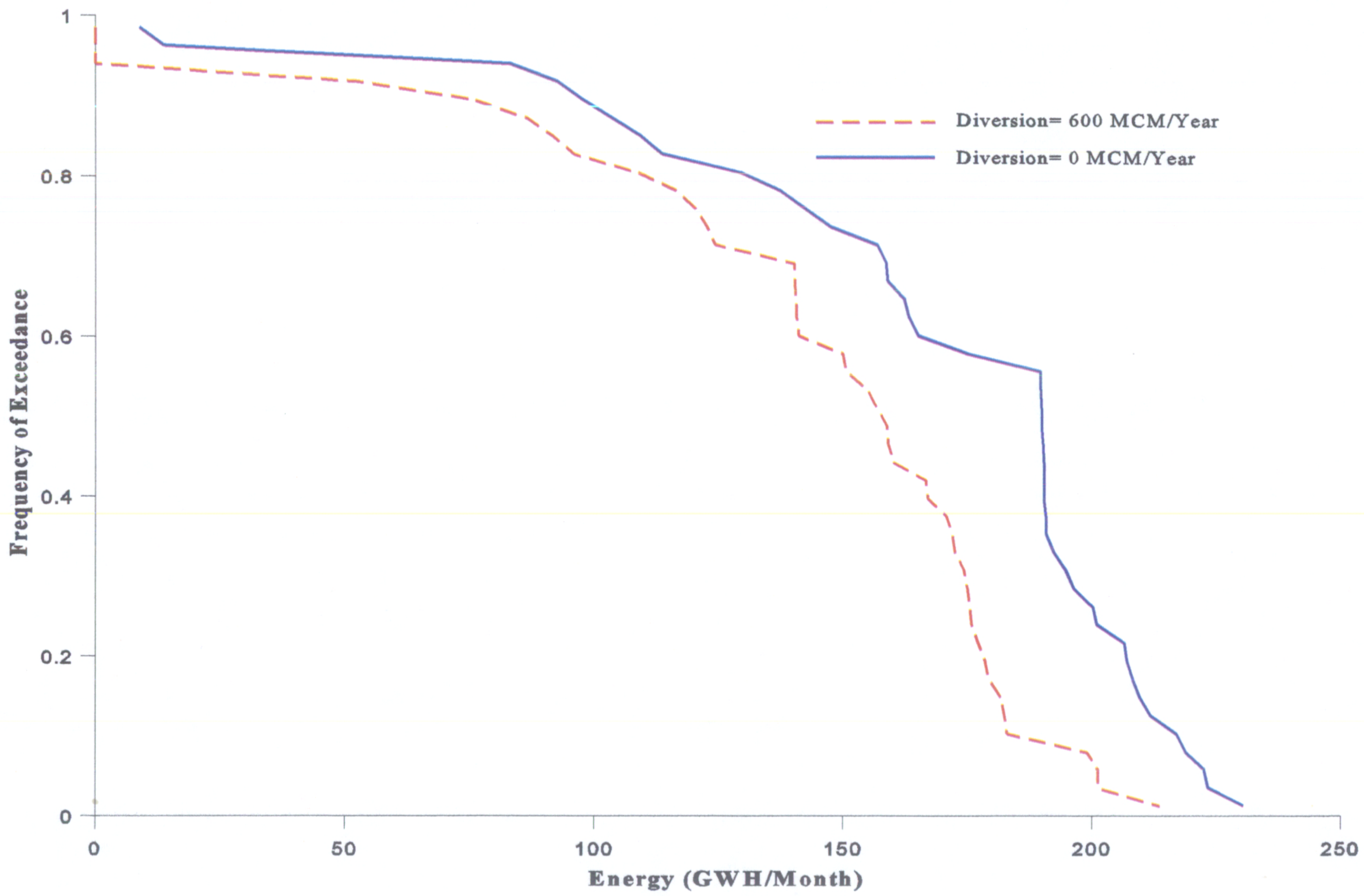

Figure 4.33: Energy Frequency of Exceedance; September

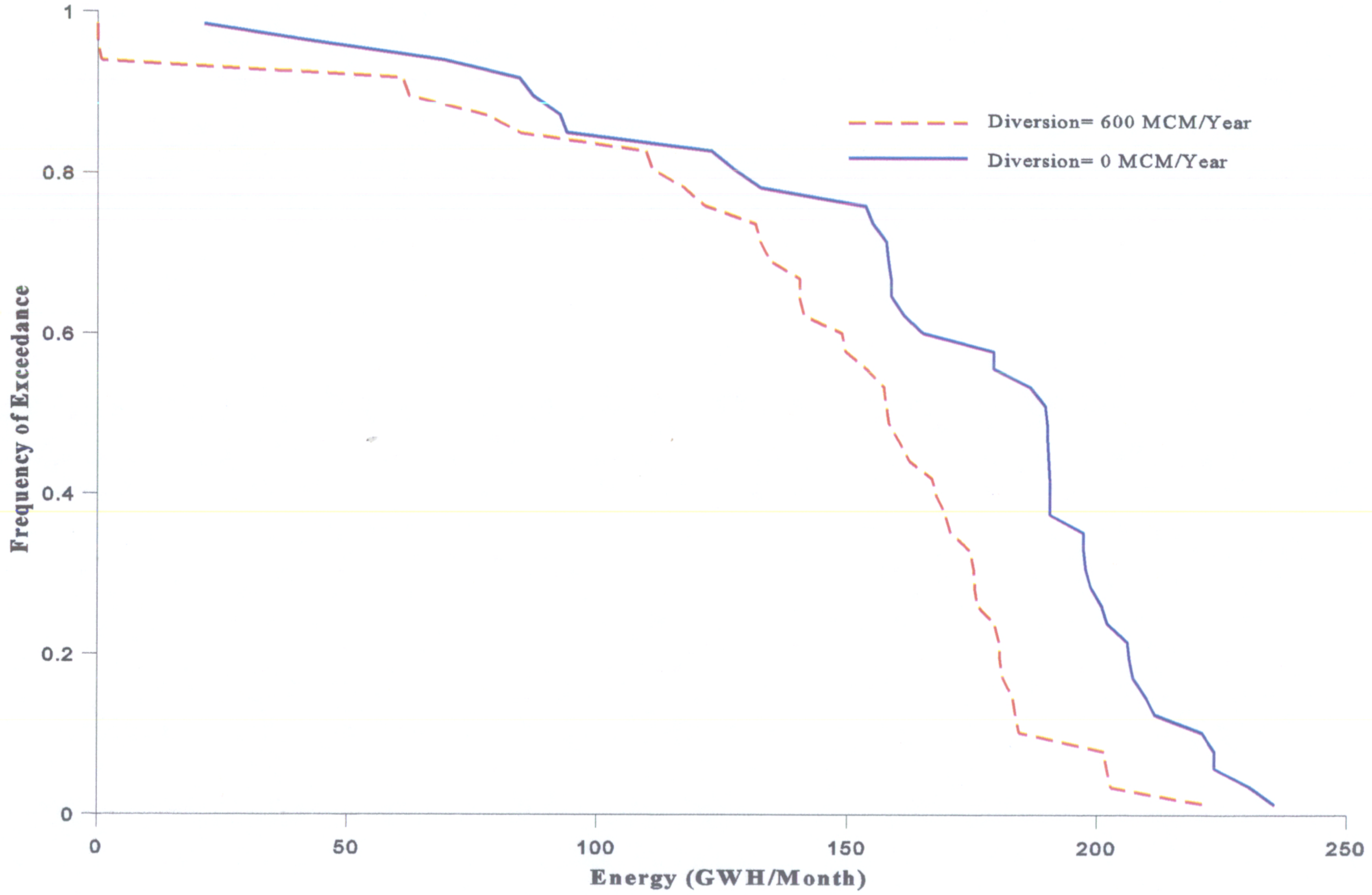

Figure 4.34: Energy Frequency of Exceedance; October

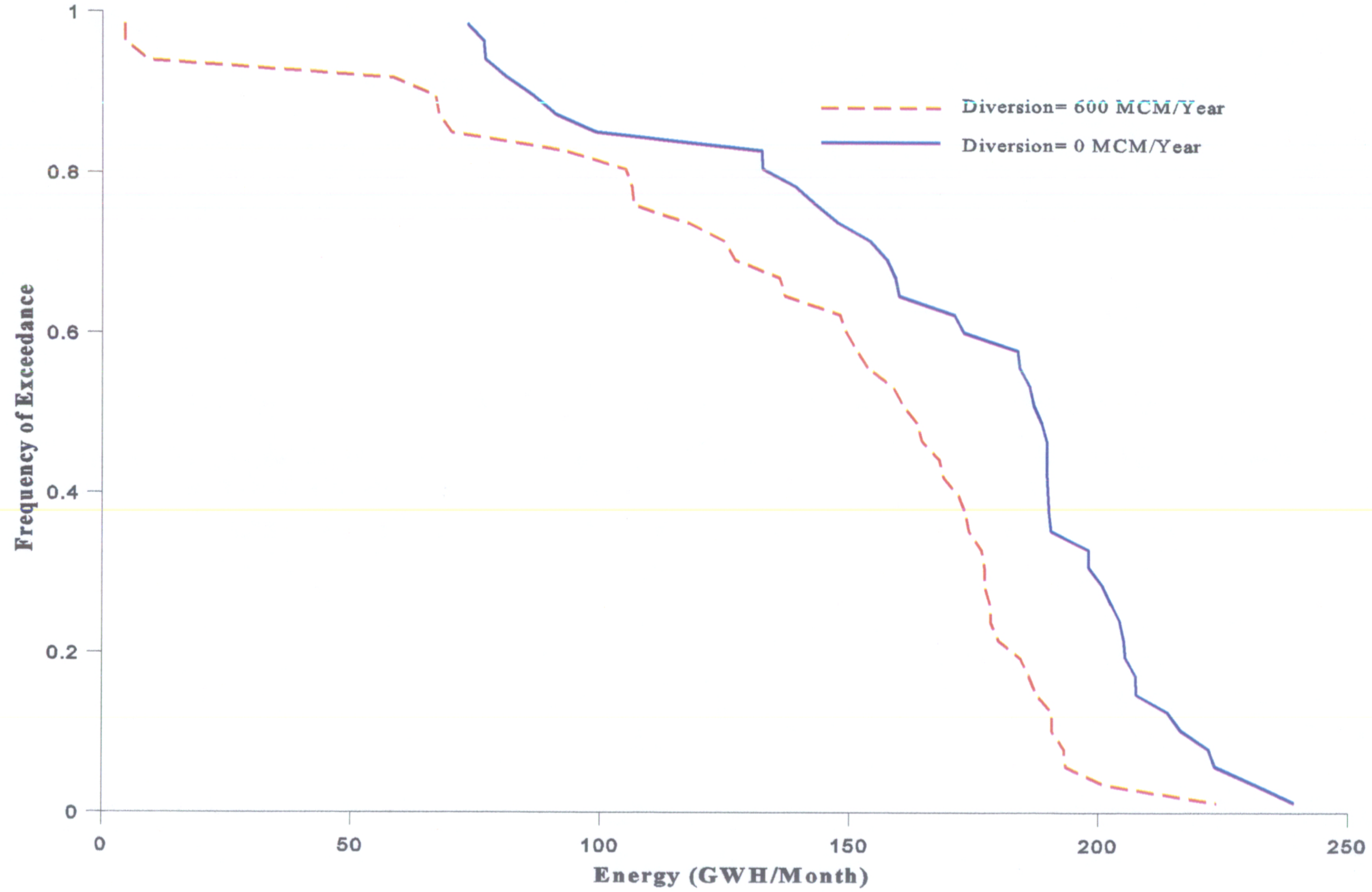

Figure 4.35: Energy Frequency of Exceedance; November

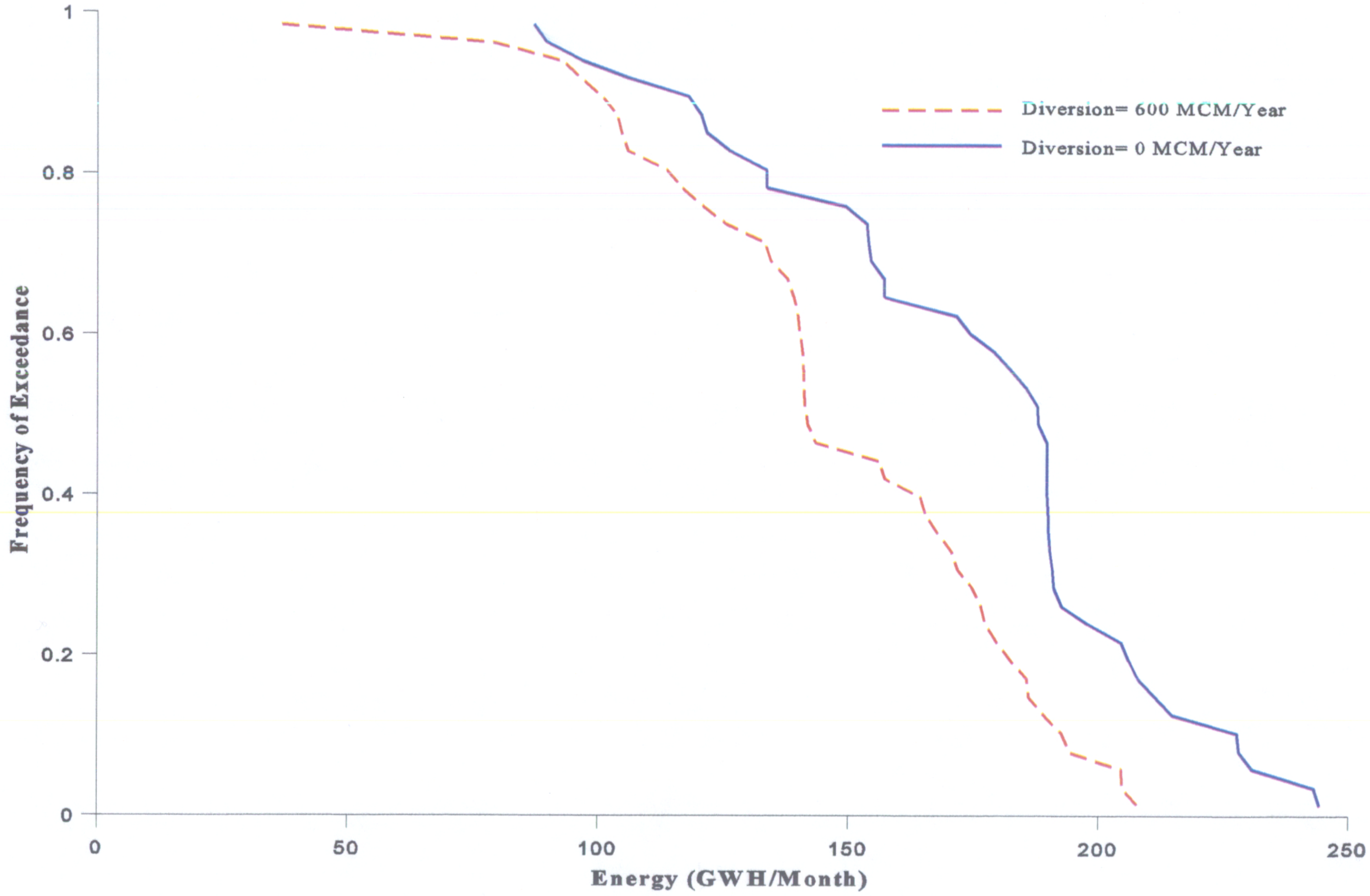

Figure 4.36: Energy Frequency of Exceedance; December

CHAPTER 5

CONCLUSIONS AND FURTHER RESEARCH RECOMMENDATIONS

This study indicates that the proposed water diversion will not significantly affect the ability of the Acheloos system to meet its present water supply requirements. It may, however, place limitations on the extent of future agricultural developments. These limitations were not quantified in this report, but can be investigated using the existing models. An important observation is that the above conclusions and those that follow are valid under the condition that the system is operated by the ELQG control model. The results are expected to be more adverse when the system is operated based on heuristic rules.

With regard to energy generation, the consequences are more serious. Annual energy generation is expected to decline by 15%, while for some months, generation will most likely decrease by 25%. In this study, the emphasis has been on the reliability of hydropower capacity. Perhaps, a more important impact metric is the *value* of energy. Hydropower benefits accrue from hydropower capacity as well as energy. In peaking hydro systems, the annual economic value of hydropower capacity is nearly four times the value of energy generated. The value of capacity is the private sector cost to construct thermal generation facilities to replace the dependable capacity of the hydro system. The value of energy is the fuel cost of replacing hydroelectric energy using thermal facilities. A study which quantifies the net increase or decrease of hydro electric energy value would be very useful.

Regarding the diversion impacts, it would be interesting to perform a similar study for the Thessalia region to quantify the anticipated benefits. This would require the development of control and control-simulation models for all Thessalia reservoirs which stand to gain by the water transfer. Since all power facilities in Greece constitute a unified system owned and operated by the Government, at least from a power standpoint, the net diversion impact could be assessed by summing up the benefits and costs. Moreover, it would be useful to investigate whether the storage in Thessalia could support a seasonal reallocation of the diversion amounts. More specifically, if it were possible to divert water earlier in the year and store it in certain headwater reservoirs in Thessalia for a month or two, it would considerably mitigate the diversion consequences. This scenario would better synchronize the timing of the diversion with the timing of the high Acheloos flows (Chapter 2) and would increase the system reliability and resilience.

Although the control model in this study was developed to address the impacts of the planned diversion, it could also be used as a decision support system to guide the real- time operations of the Acheloos River. To this end, it would have to be expanded to include mid- and short-term control models designed to operate on daily and hourly intervals, and would have to be coupled with physically based forecasting models using on-site and possibly remote (i.e., radar and satellite) data. This decision system would make it possible for the water and power authorities to explore the impacts of various operational policies and select the one which most effectively meets the needs of the system users. An example of a similar decision system developed and implemented by the Georgia Tech research team for the Nile River Basin is described by *Georgakakos et al., 1995d,e,f,g,h.*

Along this research line, to examine the benefits of better inflow forecasting, we performed an additional control-simulation experiment (under the diversion scenario) assuming that the control model has access to perfect 12-month forecasts of the upcoming inflows. The monthly energy generation frequency curves for this run are plotted together with the curves already discussed on Figures 5.1 through 5.12 and show that forecasting improves system operations. As can be seen by the shape of these curves, forecasting increases the reliability of energy generation by making a certain energy amount available for a larger percentage of time. (In some instances, the reliability of the perfect forecast curves approaches and even exceeds that of the zero diversion scenario.) In fact, this improvement would be much more pronounced if the discharge capacity of the turbines were more restrictive. However, for monthly time scales, the assumption that the turbines could operate for 24 hours a day throughout the entire month diminishes the possibility of spillage. On the other hand, for shorter time scales, the ability to anticipate high floods is critical for avoiding spillage and loss of energy.

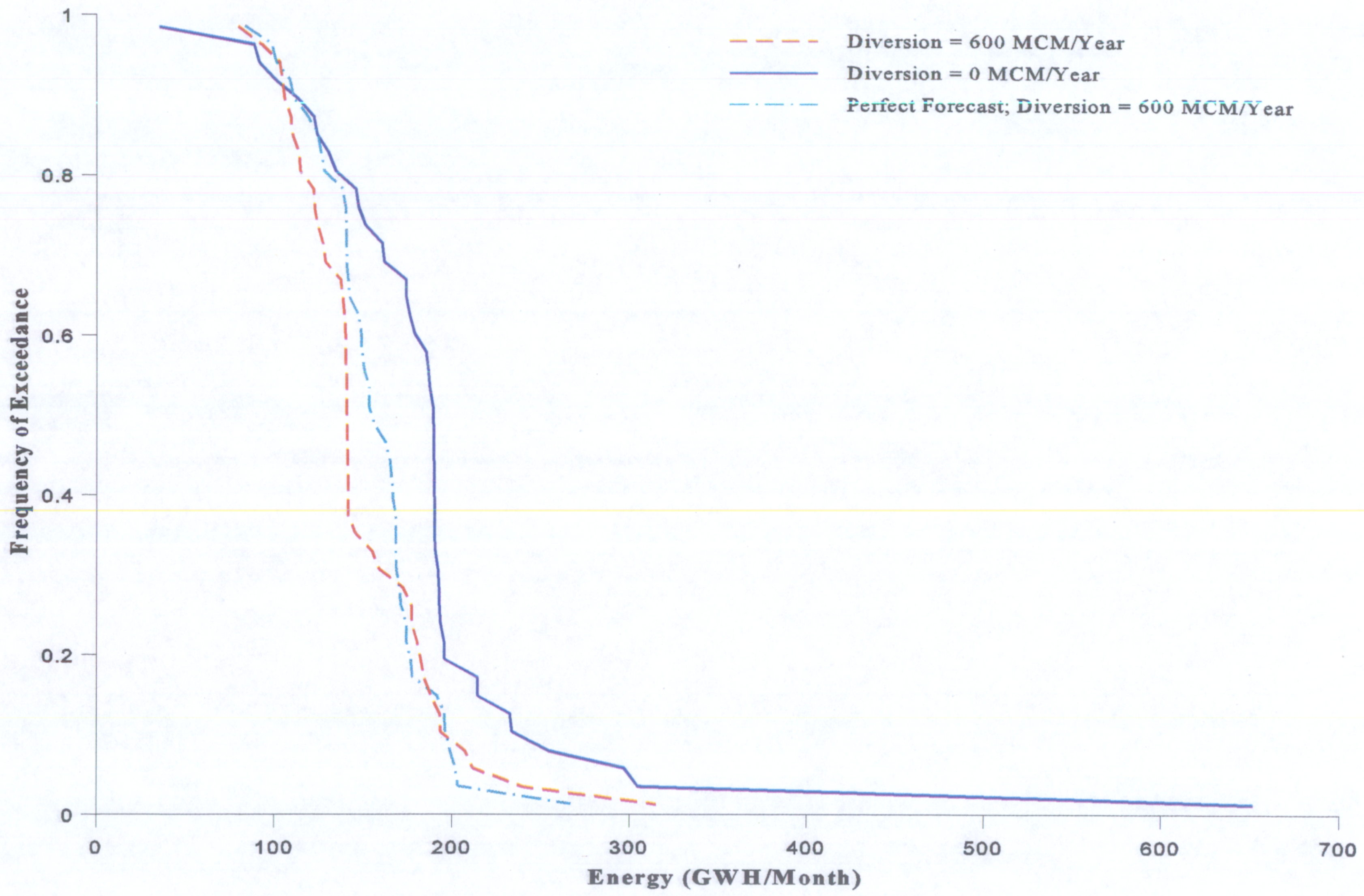

Figure 5.1: Energy Frequency of Exceedance; Perfect Forecast Comparison; January

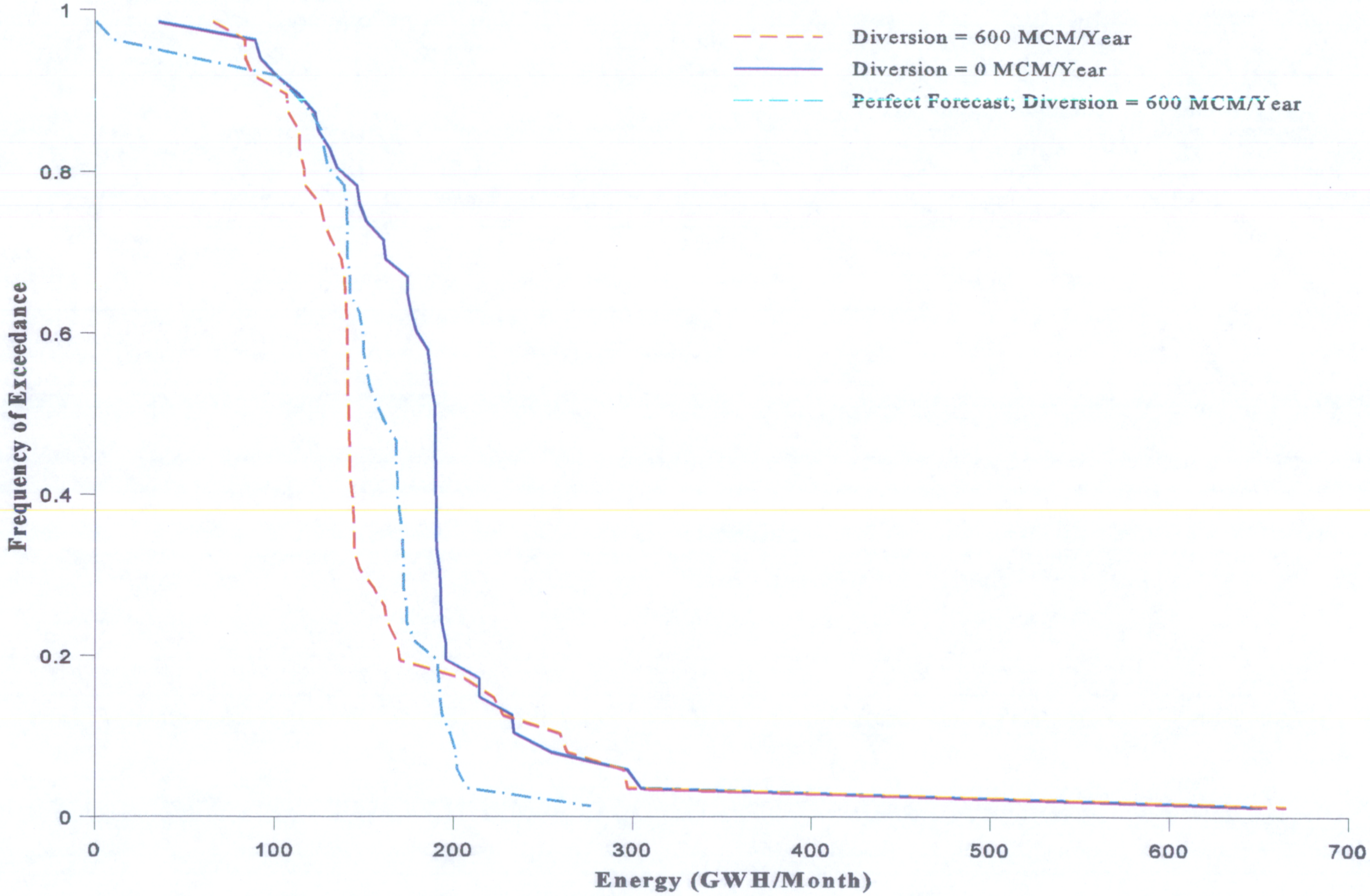

Figure 5.2: Energy Frequency of Exceedance; Perfect Forecast Comparison; February

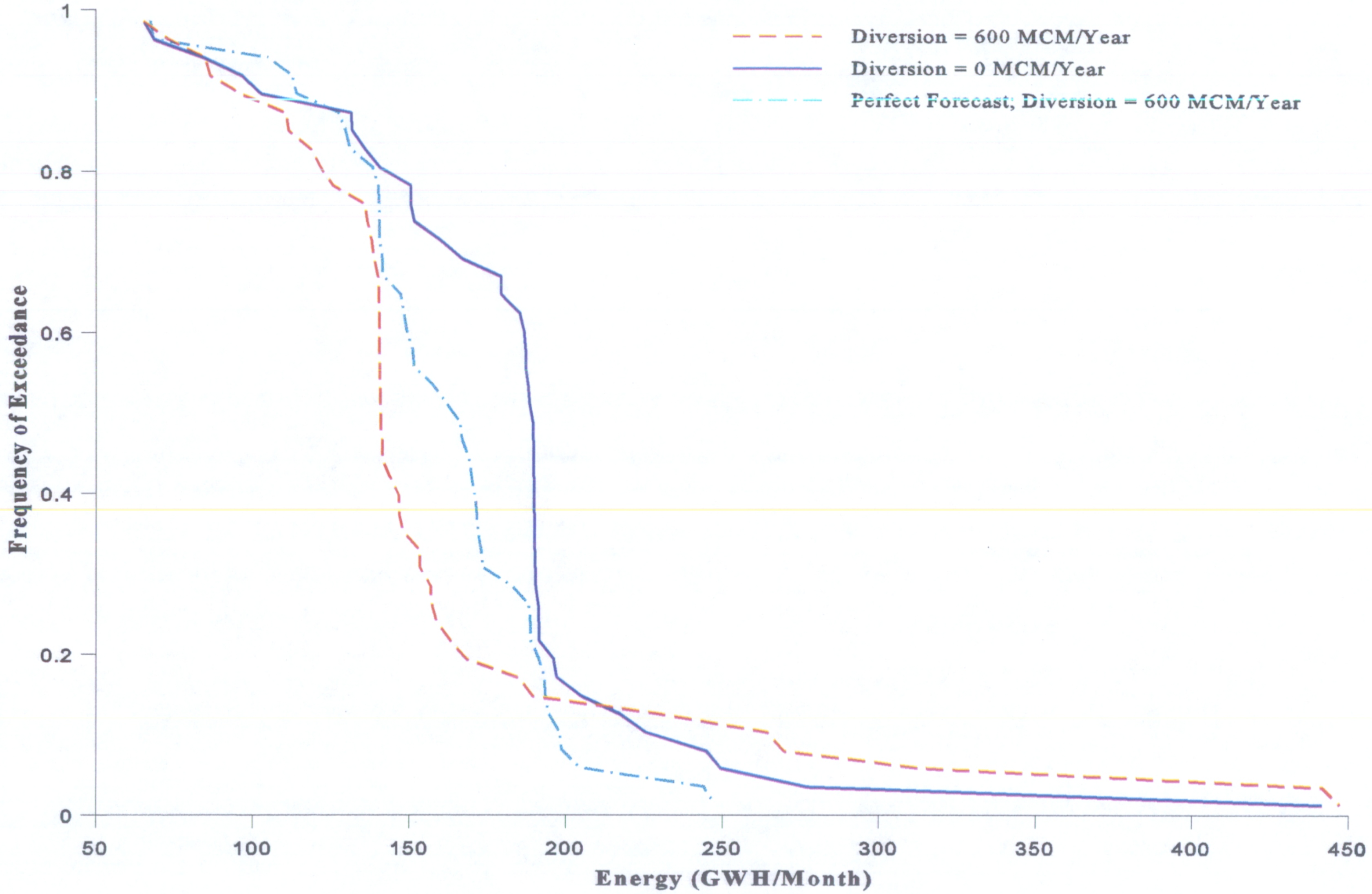

Figure 5.3: Energy Frequency of Exceedance; Perfect Forecast Comparison; March

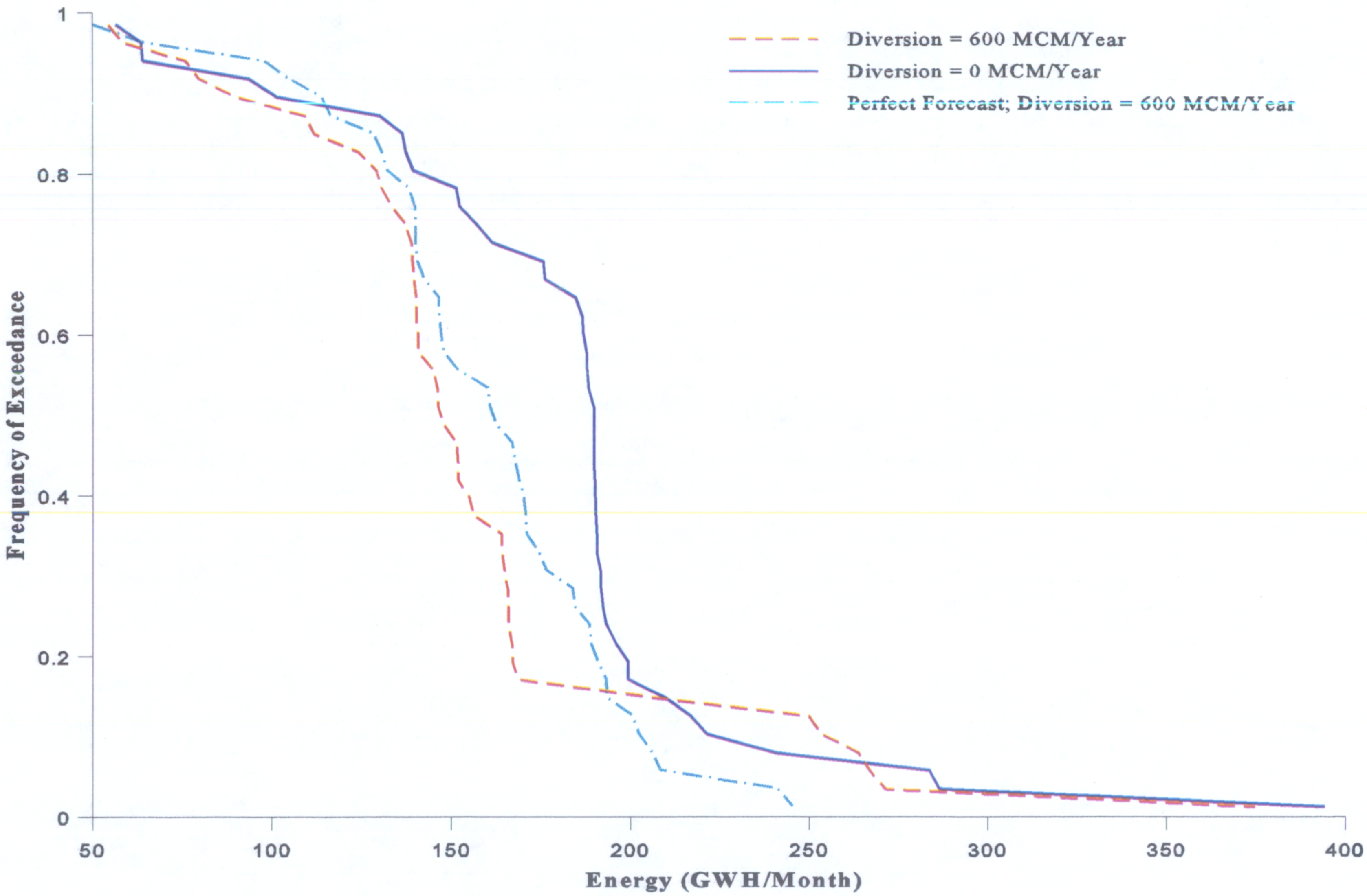

Figure 5.4: Energy Frequency of Exceedance; Perfect Forecast Comparison; April

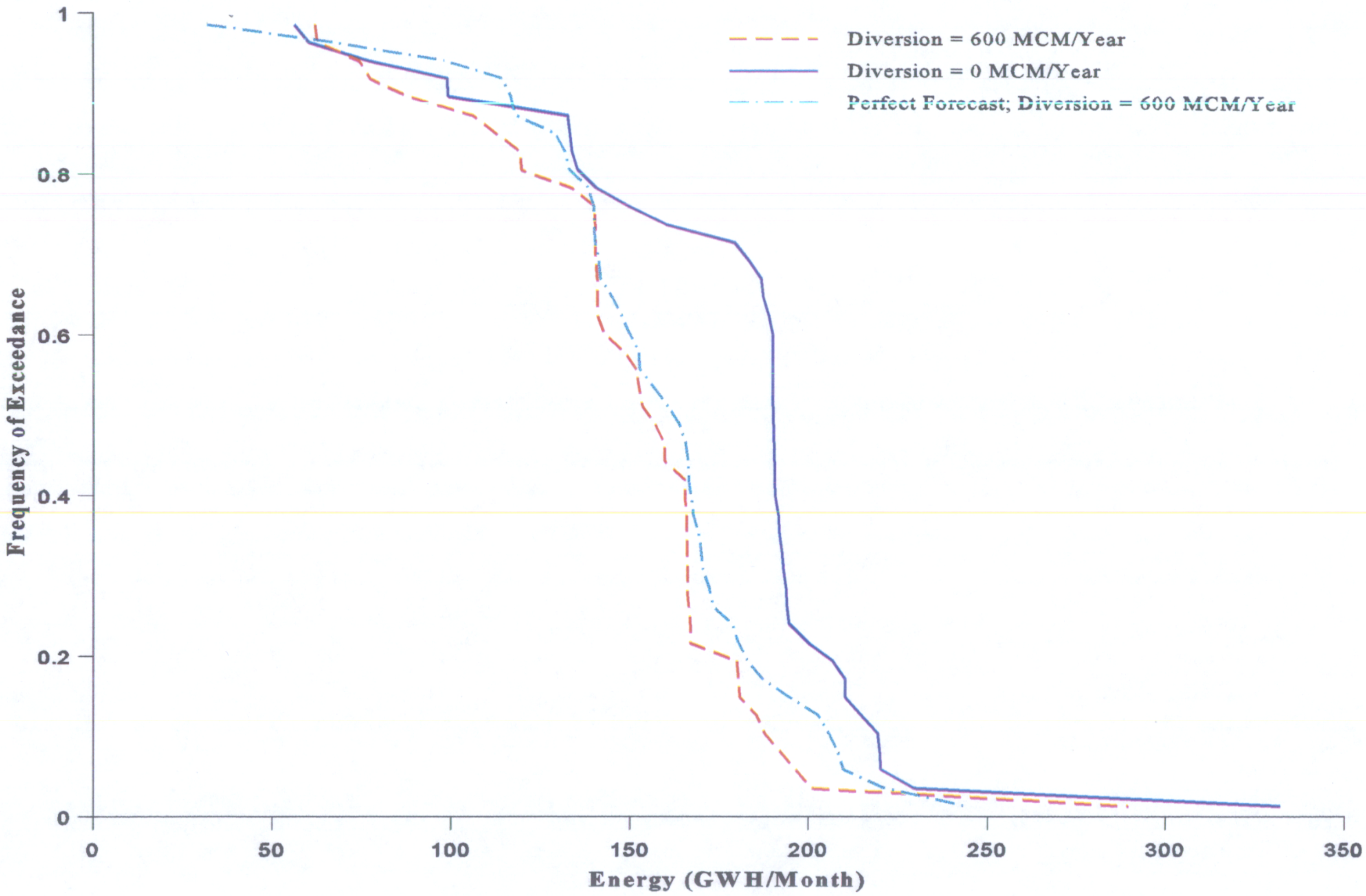

Figure 5.5: Energy Frequency of Exceedance; Perfect Forecast Comparison; May

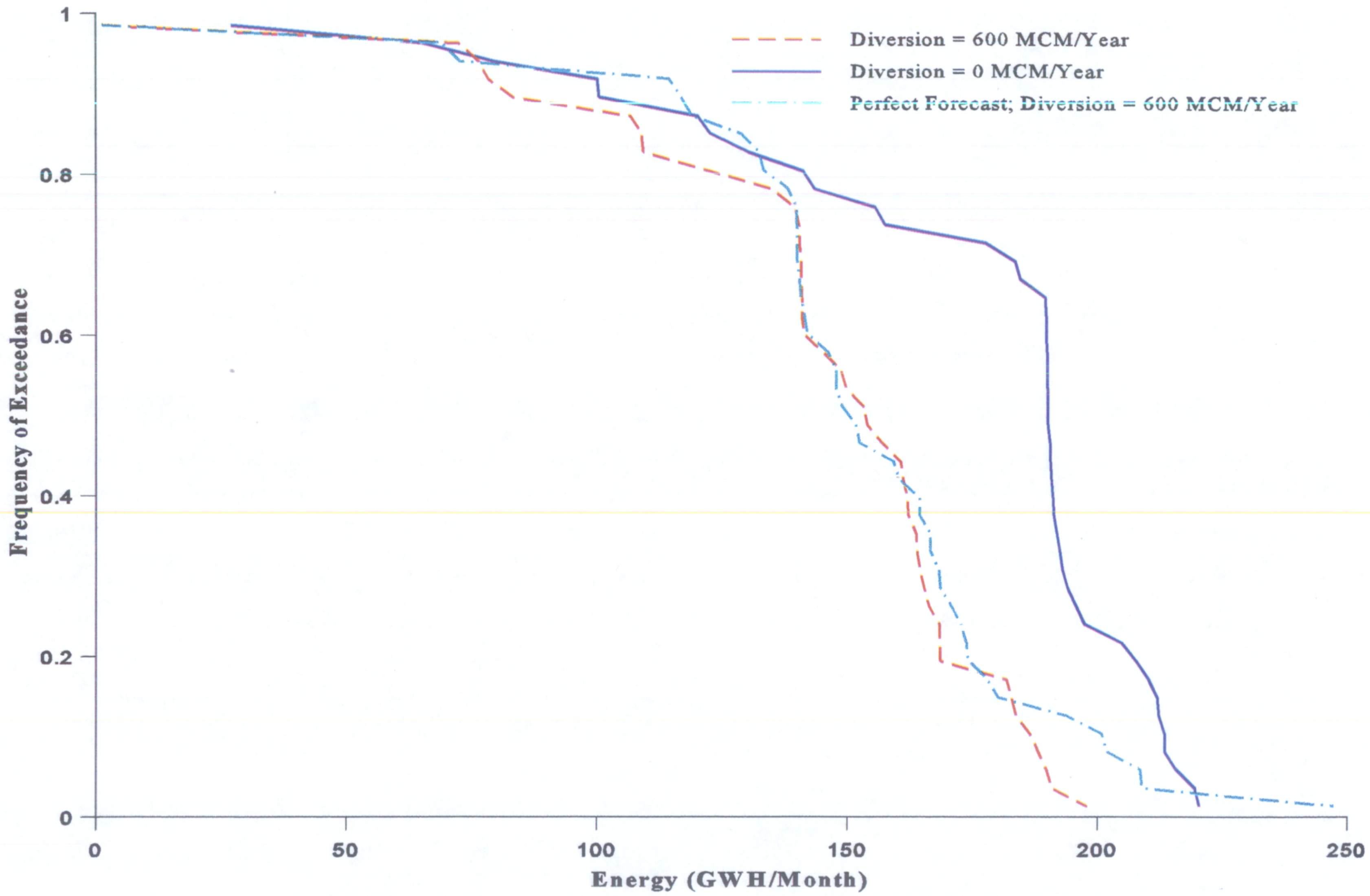

Figure 5.6: Energy Frequency of Exceedance; Perfect Forecast Comparison; June

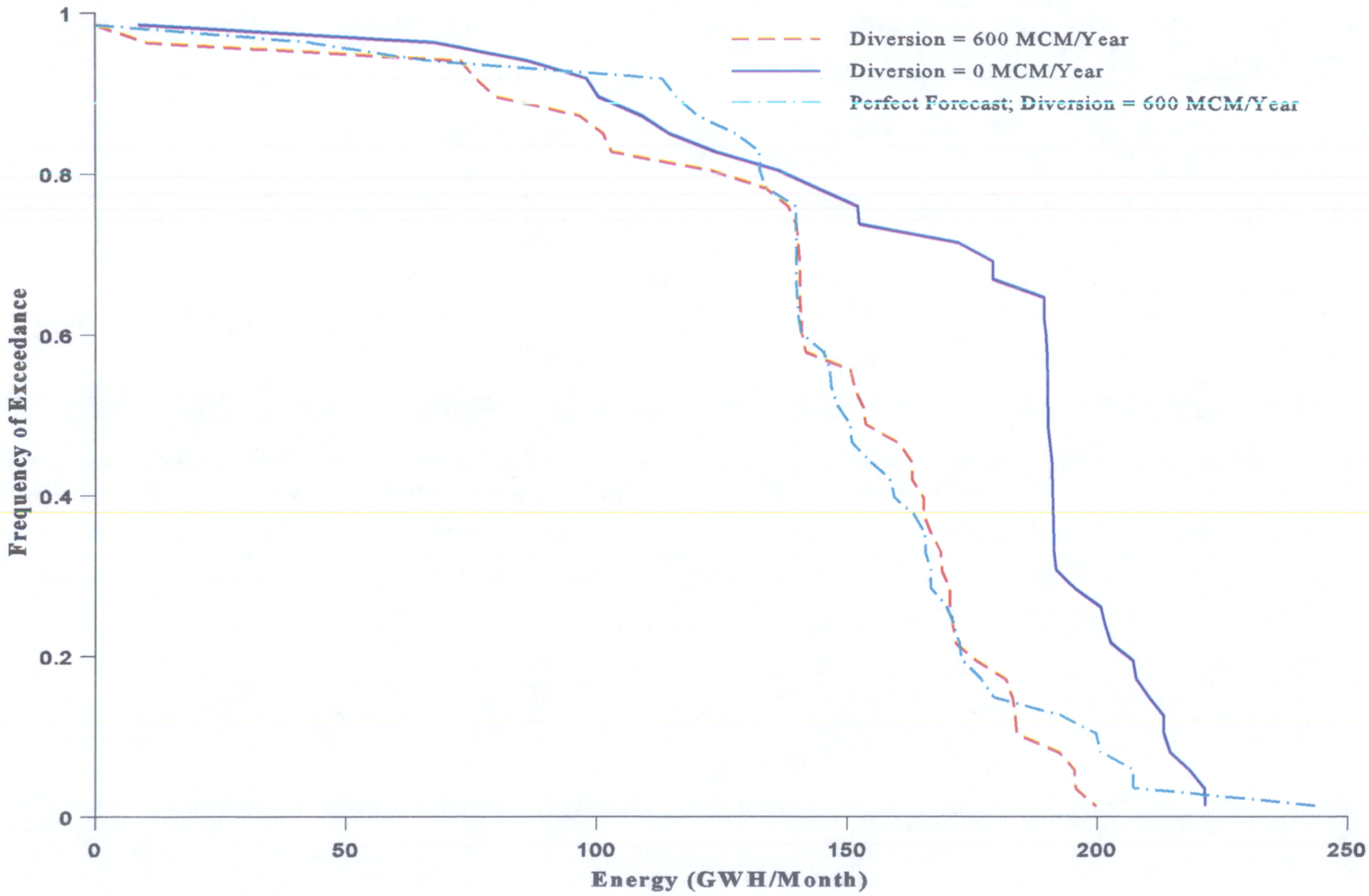

Figure 5.7: Energy Frequency of Exceedance; Perfect Forecast Comparison; July

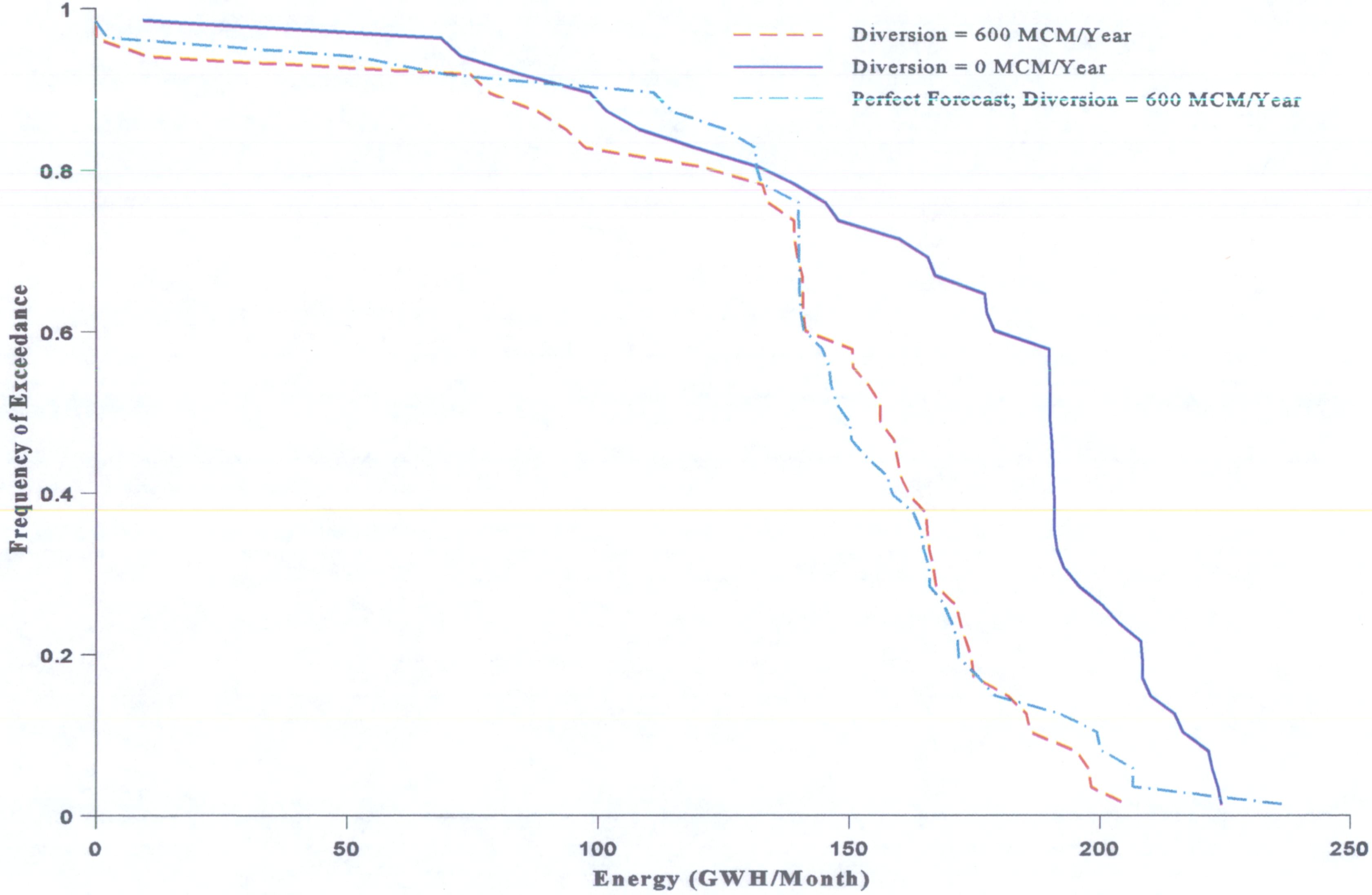

Figure 5.8: Energy Frequency of Exceedance; Perfect Forecast Comparison; August

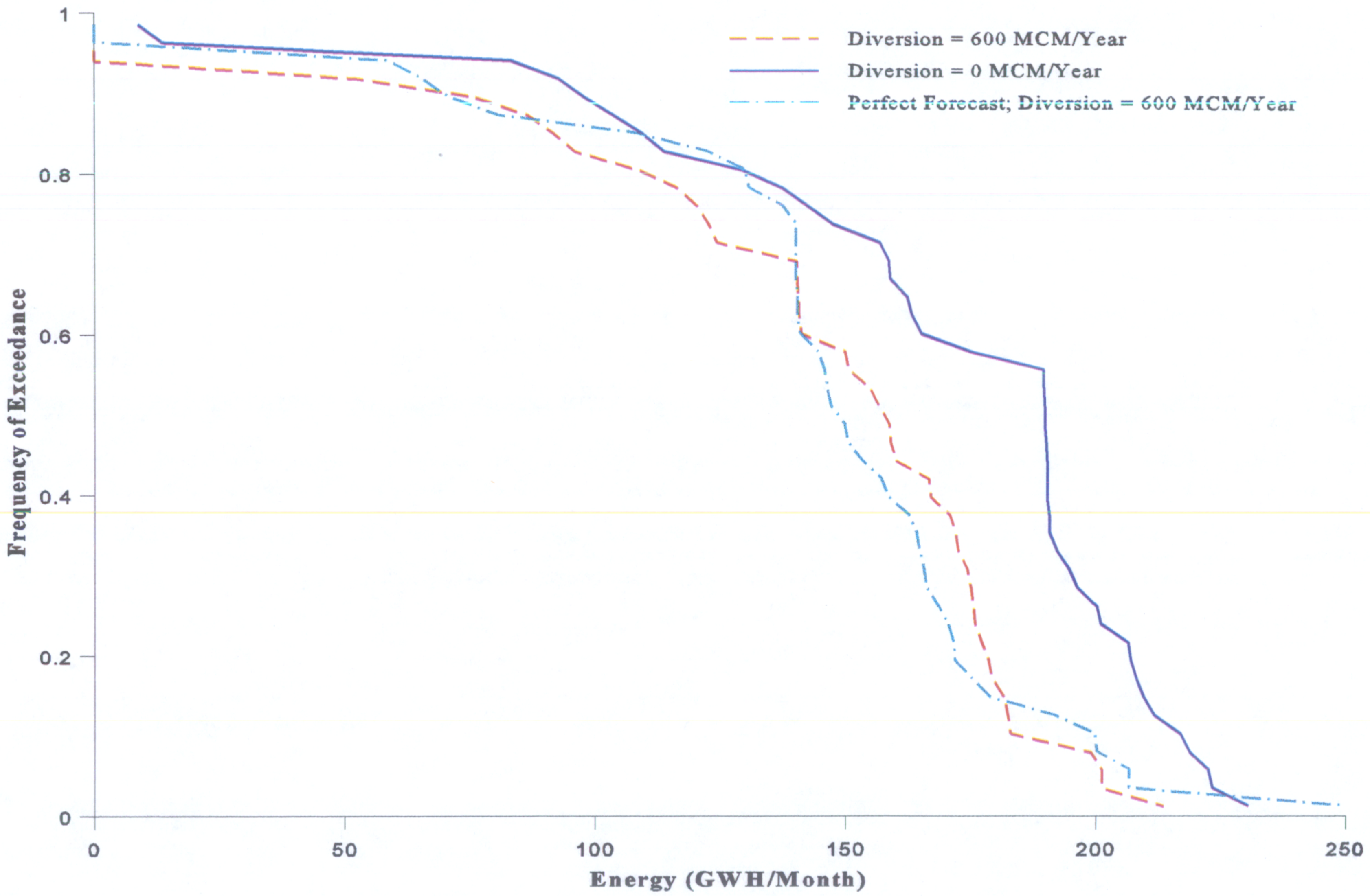

Figure 5.9: Energy Frequency of Exceedance; Perfect Forecast Comparison; September

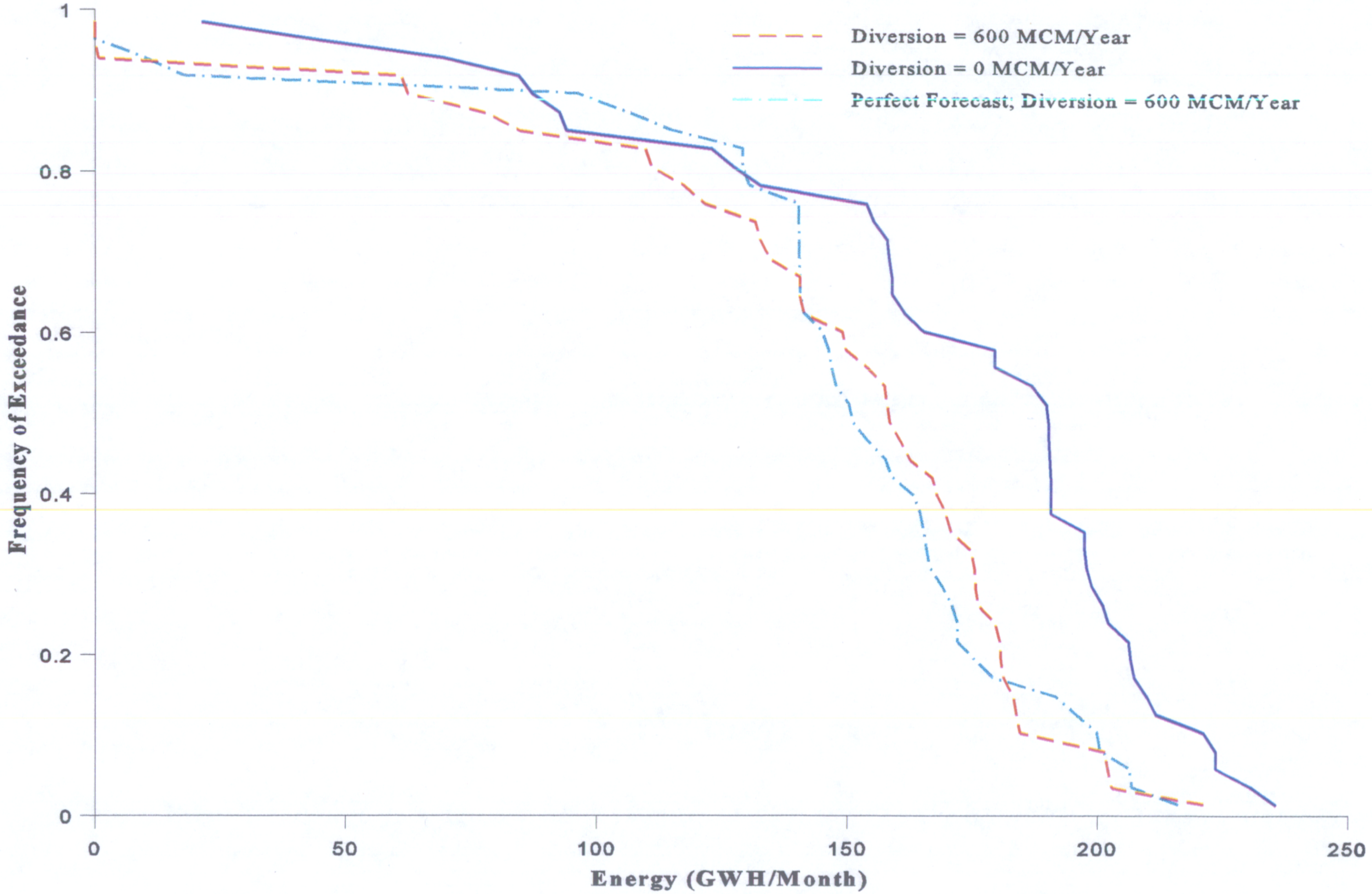

Figure 5.10: Energy Frequency of Exceedance; Perfect Forecast Comparison; October

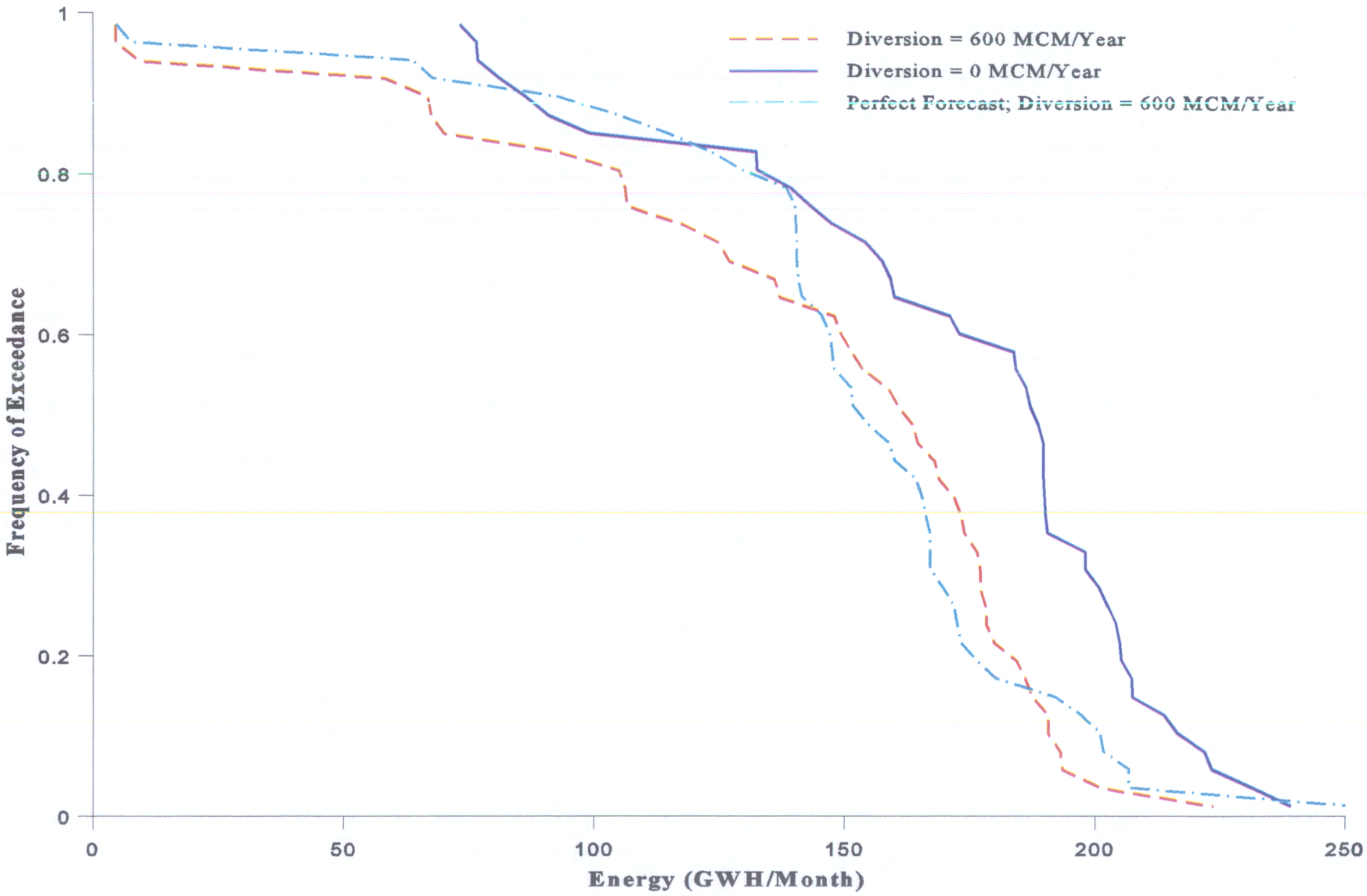

Figure 5.11: Energy Frequency of Exceedance; Perfect Forecast Comparison; November

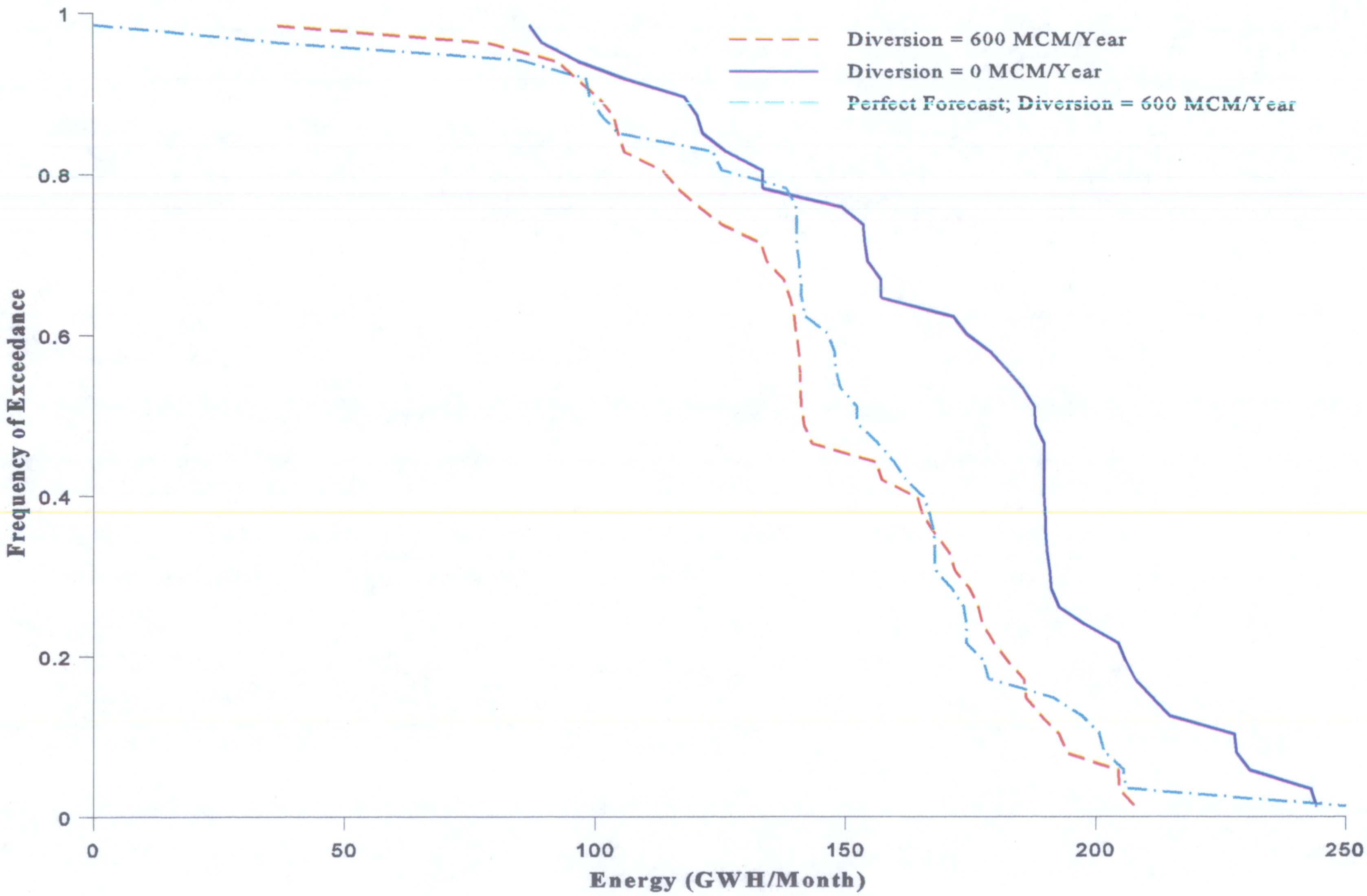

Figure 5.12: Energy Frequency of Exceedance; Perfect Forecast Comparison; December

REFERENCES

Georgakakos, A.P., " Extended Linear Quadratic Gaussian (ELQG) control: Further extensions," *Water Resources Research*, 25(2), 191-201, 1989.

Georgakakos, A.P., "Computer-Aided Management of the Southeastern U.S. Reservoir System," in " *Decision Support Systems*," D.P. Loucks, ed., NATO ASI Series, Vol. G 26, pg. 407-428, 1991.

Georgakakos, A. P., "Operational tradeoffs in reservoir control," *Water Resources Research*, 3801-3819, Vol. 29, Nov. 1993.

Georgakakos, A.P. and D. Marks, A New Method for the Real-Time Operation of Reservoir System, *Water Resources Research*, 23(7), 1376-1390, 1987.

Georgakakos, A.P., Yao, H., and Y. Yu, "A Control Model for Dependable Hydropower Capacity Optimization," forthcoming, *Water Resources Research*, 1995a.

Georgakakos, A.P., H. Yao, and Y. Yu, "A Control Model for Hydroelectric Energy Optimization," forthcoming, *Water Resources Research*, 1995b.

Georgakakos, A.P., H. Yao, and Y. Yu, "A Control Model for Hydroelectric Energy Value Optimization," forthcoming, *ASCE J. for Wat. Res. Plan. and Mgt.*, 1995c.

Georgakakos, A.P., and H. Yao, "A Decision Support System for the Equatorial Lakes," Technical Report No. GIT/CEE-HYDRO-95-1, School of Civil and Environmental Engineering, Georgia Tech, Atlanta, July 1995d, 185p.

Georgakakos, A.P., H. Yao, and Y. Yu, "A Decision Support System for the High Aswan

Dam," Technical Report No. GIT/CEE-HYDRO-95-2, School of Civil and Environmental Engineering, Georgia Tech, Atlanta, July 1995e, 307p.

Georgakakos, A.P., Y. Yu, and H. Yao, "Inflow Forecasting Models for the High Aswan Dam," Technical Report No. GIT/CEE-HYDRO-95-3, School of Civil and Environmental Engineering, Georgia Tech, Atlanta, July 1995f, 208p.

Georgakakos, A.P., and H. Yao, "Nile Basin Management 1.0, High Aswan Dam Models, User Manual," Technical Report No. GIT/CEE-HYDRO-95-4, School of Civil and Environmental Engineering, Georgia Tech, Atlanta, July 1995g, 111p.

Georgakakos, A.P., and H. Yao, "Nile Basin Management 1.0, Equatorial Lake Models, User Manual," Technical Report No. GIT/CEE-HYDRO-95-5, School of Civil and Environmental Engineering, Georgia Tech, Atlanta, July 1995h, 47p.

APPENDIX A

RESERVOIR DATA AND CHARACTERISTIC CURVES

A.1 Elevation vs. Storage Relationships

Table A.1.1: Elevation vs. Storage Data for Kremasta

Storage (Million Cubic Meters)	Elevation (Meters)
999	227
1420	233
1750	240
2300	250
2600	255
2900	260
3300	265
3650	270
4000	275
4500	282

Table A.1.2: Elevation vs. Storage Relationship for Kremasta

Kremasta	
Curve	$H = a + b\,S + c\,\ln S + d\,/\,S + e\,S^2$
Units	H: meters S: million cubic meters
Coefficient	a = -287.049 b = -0.03171 c = +78.06547 d = -45393.4 e = +3.09E-06 f = $+4.9\text{x}10^9$
Validity Range	H: 227-282 meters S: 999-4500 million m^3
Residual Error St. Dev.	0.2 meters

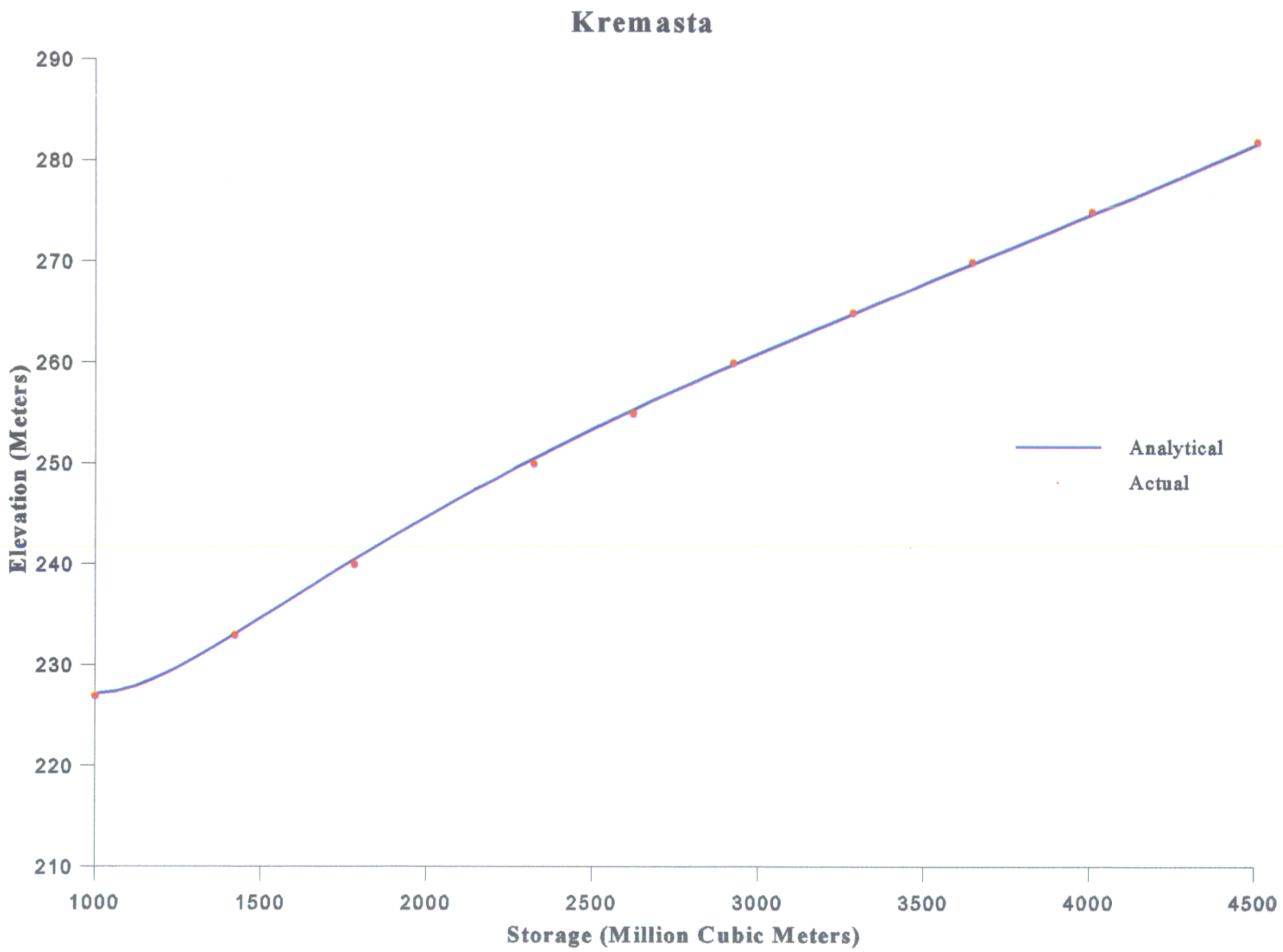

Figure A.1.1: Elevation vs. Storage Relationship for Kremasta

Table A.1.3: Elevation vs. Storage Data for Kastraki

Storage (Million Cubic Meters)	Elevation (Meters)
750	142
755	142.5
765	143
770	143.2
775	143.5
785	144
800	144.2

Table A.1.4: Elevation vs. Storage Relationship for Kastraki

Kastraki	
Curve	$H = a + b\,S + c\,\ln S + d\,/\,S + e\,S^2$
Units	H: meters S: million cubic meters
Coefficient	a = - 81281.43 b = - 0.0249 c = +9857.63 d = +16533673.75 e =+0.000243 f = -3373701022.
Validity Range	H: 142-144.2 meters S: 750-800 million m^3
Residual Error St. Dev.	0.1 meters

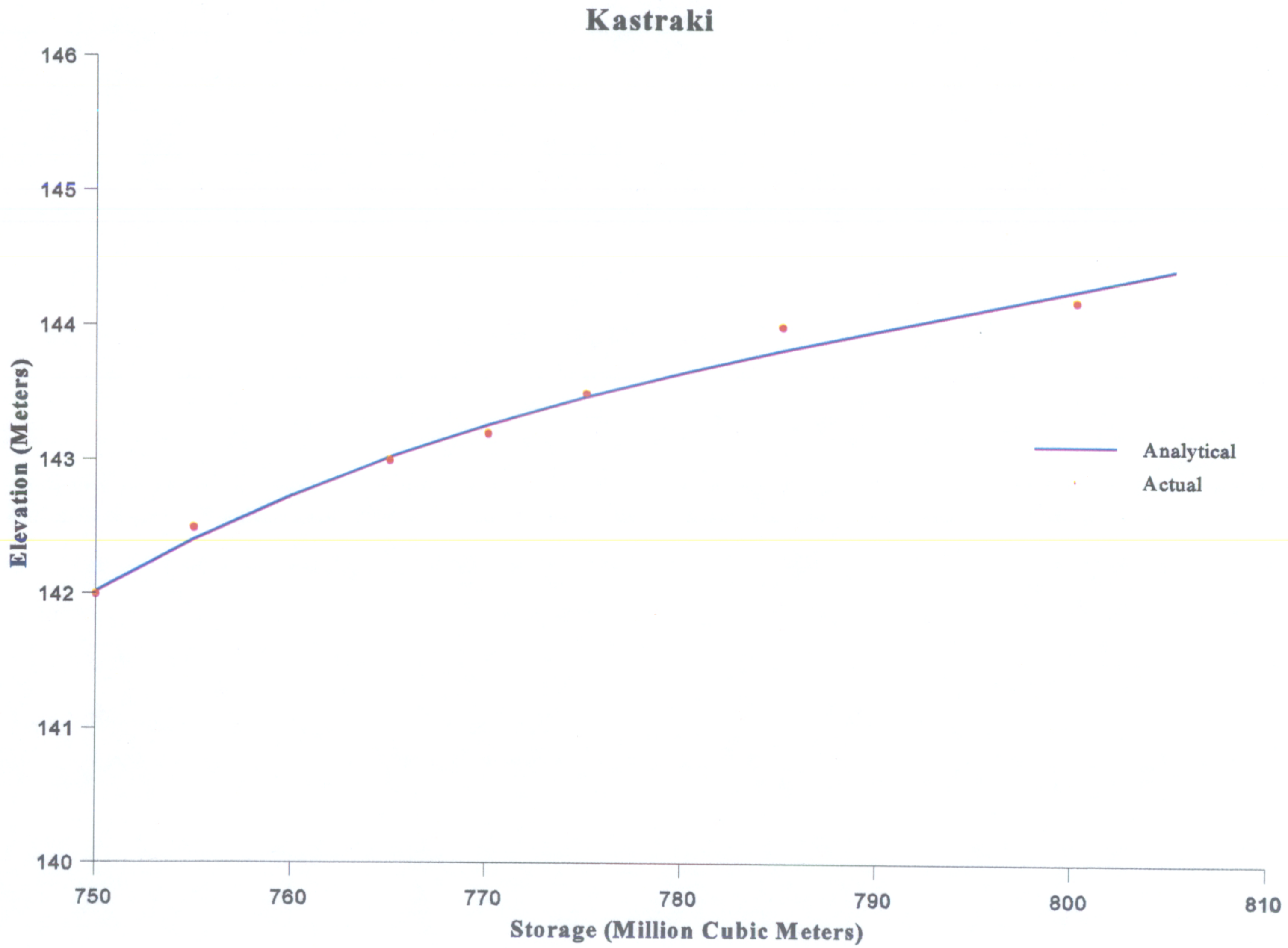

Figure A.1.2: Elevation vs. Storage Relationship for Kastraki

Table A.1.5: Elevation vs. Storage Data for Stratos

Storage (Million Cubic Meters)	Elevation (Meters)
43.16	64
55.79	66
64.21	68
84.21	70

Table A.1.6: Elevation vs. Storage Relationship for Stratos

Stratos	
Curve	H = a + b S
Units	H: meters S: billion cubic meters
Coefficient	a = +57.588 b = +0.1568627
Validity Range	H: 67-68.6 meters S: 60-70.2 million m^3
Residual Error St. Dev.	0.0 meters (linear segment between two points)

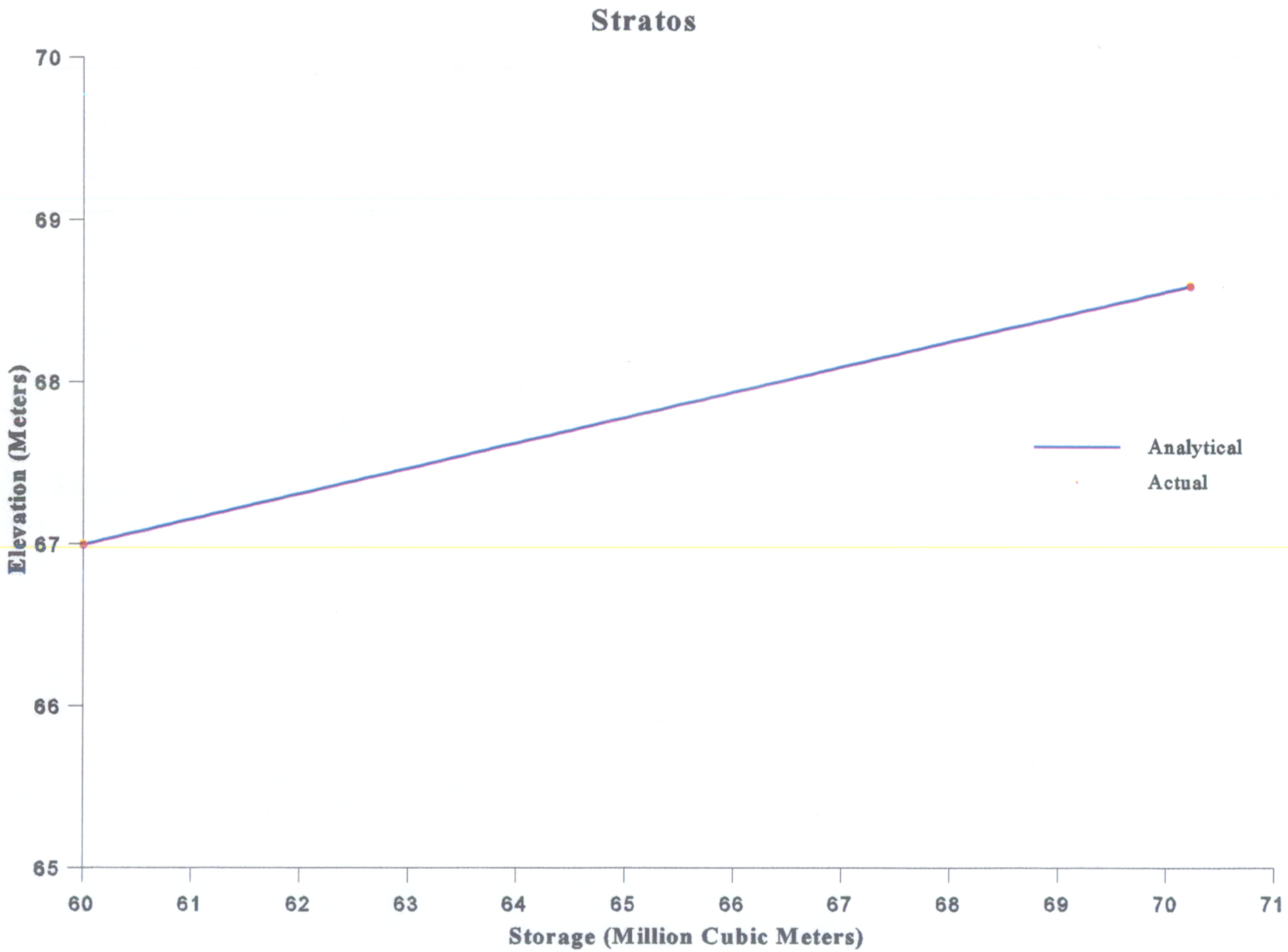

Figure A.1.3: Elevation vs. Storage Relationship for Stratos

A.2 Area vs. Storage Relationships

Table A.2.1: Area vs. Storage Data for Kremasta

Storage (Million Cubic Meters)	Area (Square Kilometers)
999	40
1420	45
1750	50
2300	58
2600	61
2900	65
3300	68
3650	71
4000	74
4500	79

Table A.2.2: Area vs. Storage Relationship for Kremasta

Kremasta	
Curve	Area = $a + b\,S + c\ln S + d / S + e\,S^2$
Units	Area: square kilometers S: million cubic meters
Coefficient	a = - 5526.22 b = - 0.226 c = +734.2 d =+896060.9 e = +1.27E-05 f= - 187927230.2
Validity Range	Area: 40-79 square kilometers S: 999-4500 million m^3
Residual Error St. Dev.	0.21 square kilometers

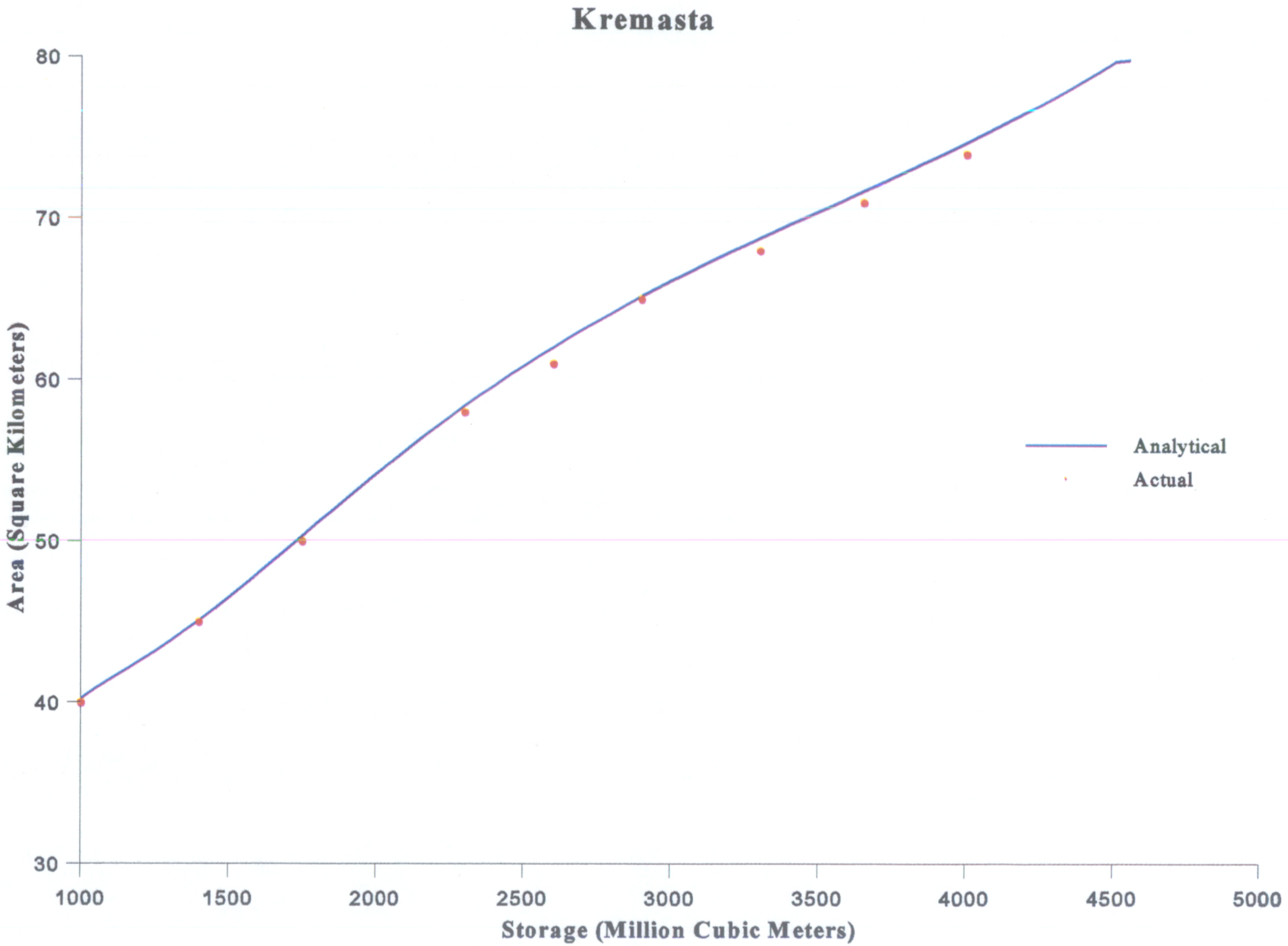

Figure A.2.1: Area vs. Storage Relationship for Kremasta

Table A.2.3: Area vs. Storage Data for Kastraki

Storage (Million Cubic Meters)	Elevation (Meters)
750	23.3
755	23.5
765	23.8
770	23.9
775	24.1
785	24.2
800	24.4

Table A.2.4: Elevation vs. Storage Relationship for Kastraki

Kastraki	
Curve	$H = a + b S + c \ln S + d / S + e S^2$
Units	H: meters S: million cubic meters
Coefficient	a = - 32148.8 b = - 0.0133 c = +3881.744 d = +6656728.7 e = +0.000113 f = -1380655872.
Validity Range	Area: 23.3-24.4 square kilometers S: 750-800 million m^3
Residual Error St. Dev.	0.02 square kilometers

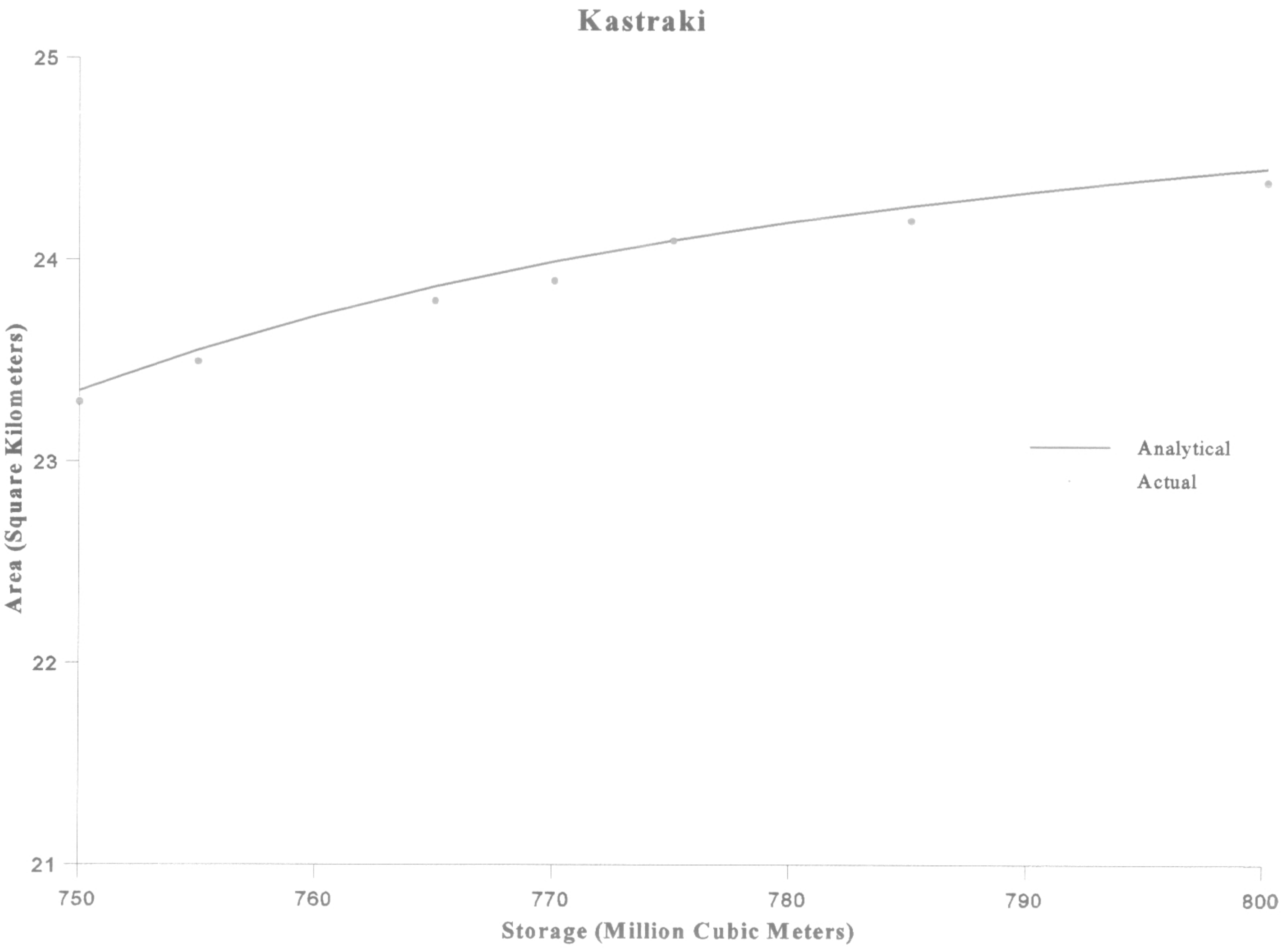

Figure A.2.2: Area vs. Storage Relationship for Kastraki

Table A.2.5: Area vs. Storage Data for Stratos

Storage (Million Cubic Meters)	Elevation (Meters)
43.16	6.11
55.79	6.63
64.21	7.05
84.21	7.58

Table A.2.6: Area vs. Storage Relationship for Stratos

Stratos	
Curve	$H = a + b\,S + c\,\mathrm{Ln}\,S + d / S$
Units	H: meters S: billion cubic meters
Coefficients	$a = -188.116$ $b = -0.3724$ $c = +47.639$ $d = +1335.51$
Validity Range	Area: 6.11-7.58 square kilometers S: 60-70.2 million m^3
Residual Error St. Dev.	0.001 meters

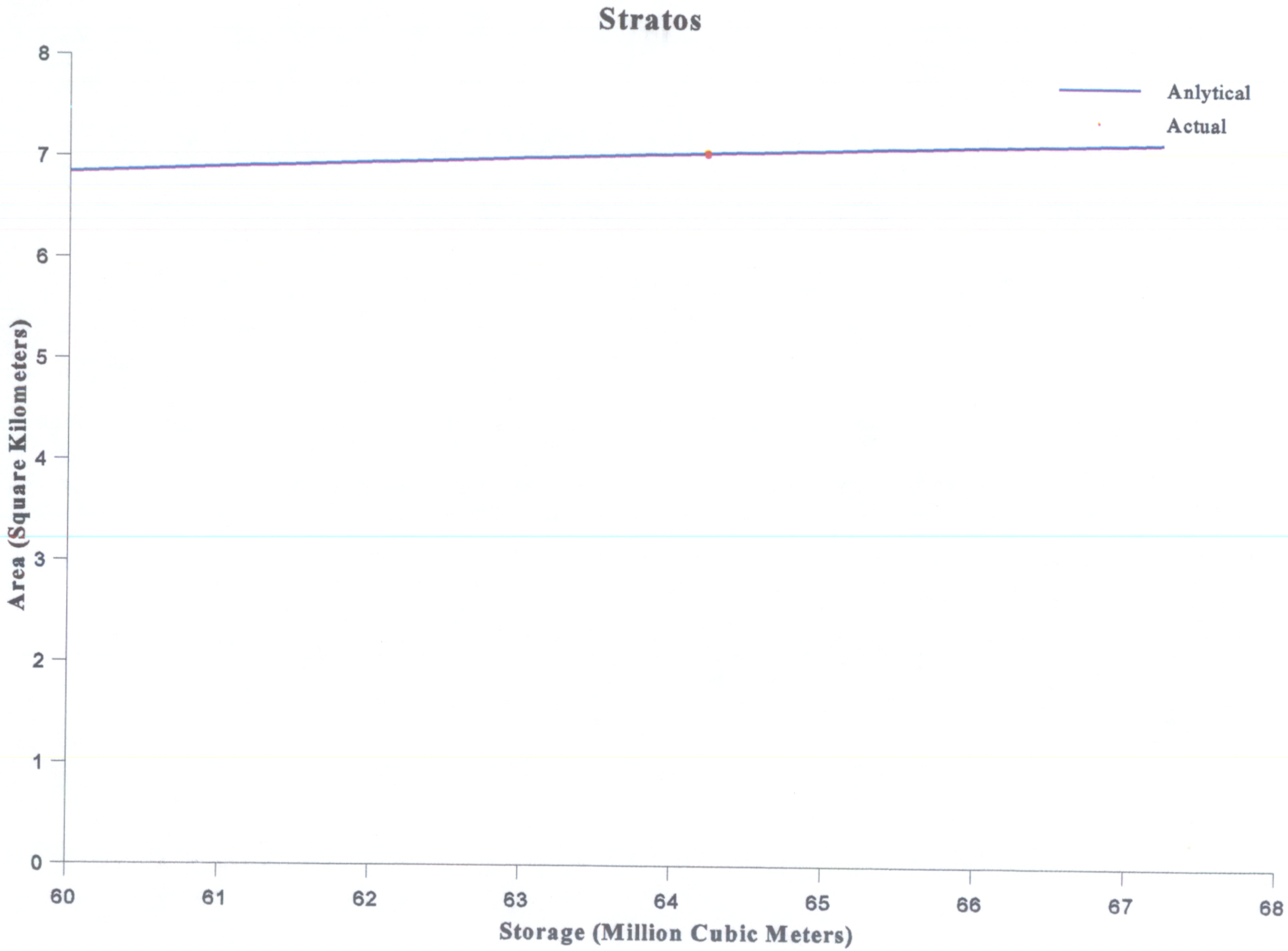

Figure A.2.3: Area vs. Storage Relationship for Stratos

A.3 Specific Generation Efficiency vs. Elevation Relationships

Table A.3.1: Specific Generation Efficiency vs. Elevation Data for Kremasta

H (m)	227	229	233	237	241	245	249	253	261	265	271	277	283
E (m^3/kwh)	5.5	5.3	5	4.7	4.4	4.2	4	3.8	3.6	3.2	3	2.8	2.6

Table A.3.2: Specific Generation Efficiency vs. Elevation Relationship for Kremasta

Kremasta	
Curve	$F = a + b H + c H^2$
Units	H: meters F: cubic meters/KWH
Coefficients	a =44.082296 b =-0.2666675 c =4.2471138×10^{-4}
Validity Range	H: 227-282 meters
Residual Error St. Dev.	0.01 cubic meters/KWH

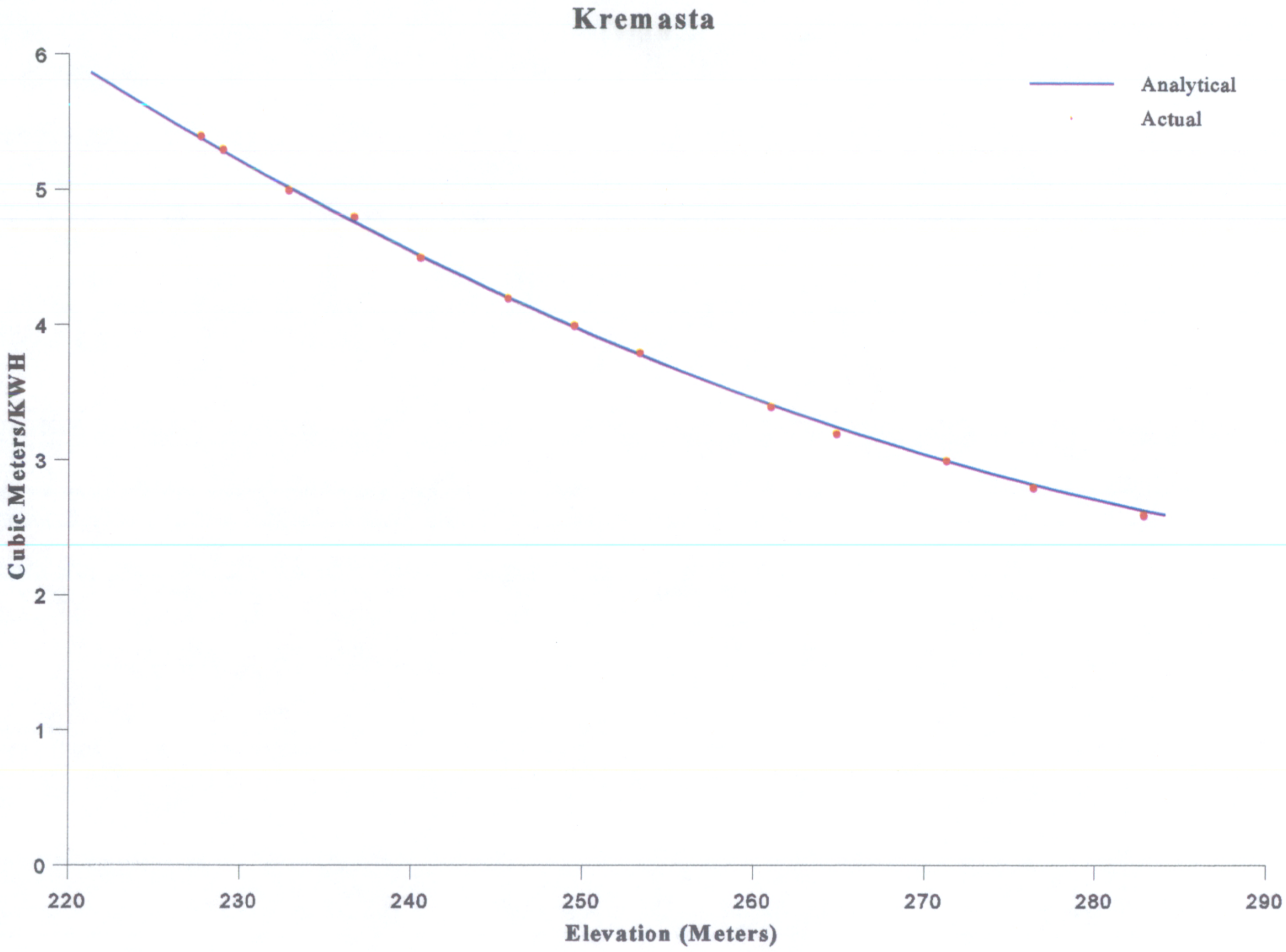

Figure A.3.1: Specific Generation Efficiency vs. Elevation Relationship for Kremasta

Table A.3.3: Specific Generation Efficiency vs. Elevation Data for Kastraki

H (meters)	142	142.5	143	143.5	144	144.5	145.0
E (cubic m^3/kwh)	5.95	5.87	5.78	5.71	5.62	5.56	5.48

Table A.3.4: Specific Discharge vs. Elevation Relationship for Kastraki

Kastraki	
Curve	$F = a + b H + c H^2$
Units	H: meters F: cubic meters/KWH
Coefficients	a = +136.0164310 b = -1.65976 c = +5.2380953 $\times 10^{-3}$
Validity Range	H: 142-144.2 meters
Residual Error St. Dev.	0.01 cubic meters/KWH

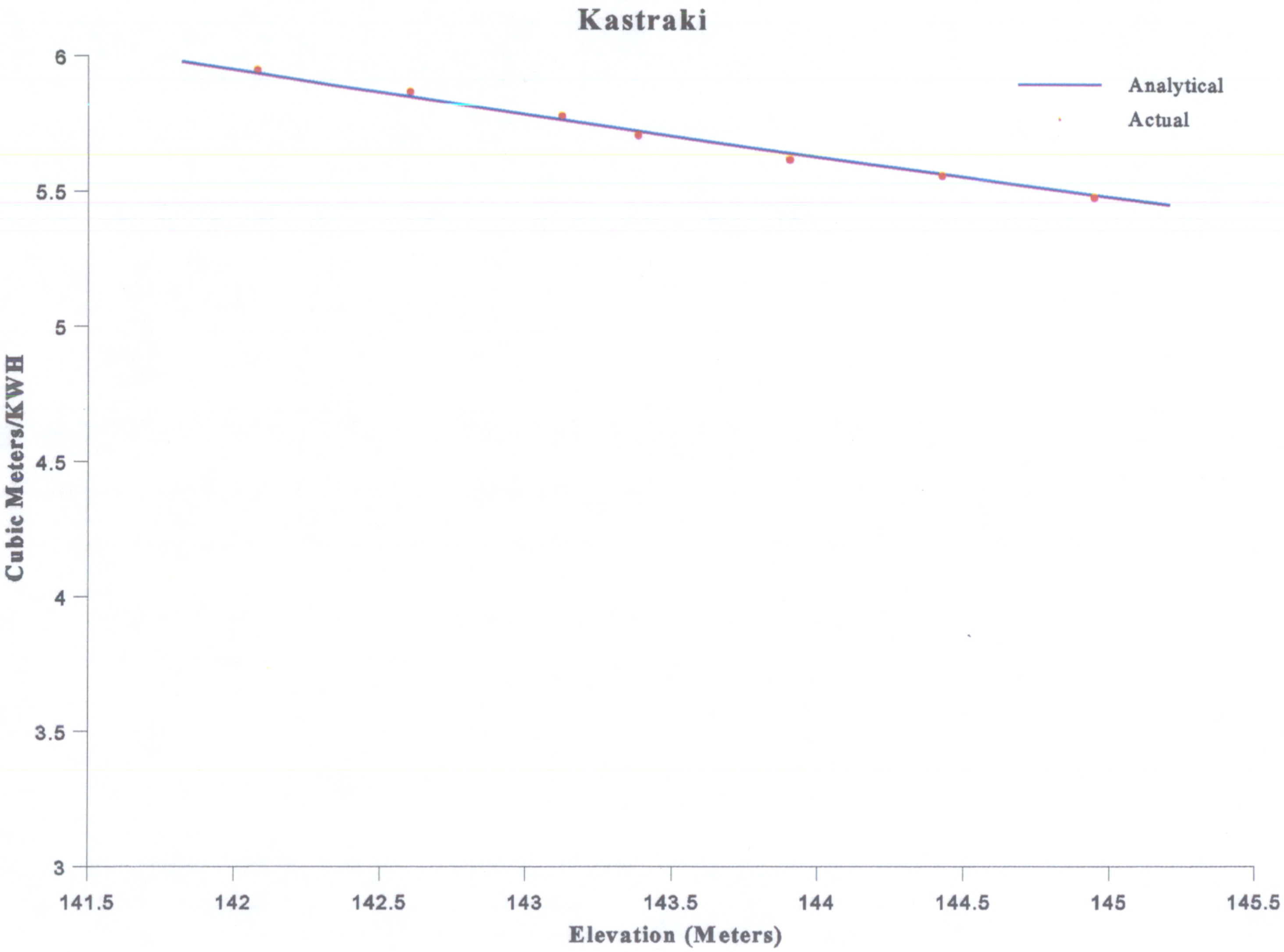

Figure A.3.2: Specific Generation Efficiency vs. Elevation Relationship for Kastraki

Table A.3.5: Specific Generation Efficiency vs. Elevation Data for Stratos

H (m)	67	67.5	68	68.5	69
E (m^3/kwh)	11.7	11.54	11.39	11.24	11.10

Table A.3.6: Specific Discharge vs. Elevation Relationship for Stratos

Stratos	
Curve	$F = a + b H + c H^2$
Units	H: meters F: cubic meters/KWH
Coefficients	a =+84.632 b = -1.8542 c = $+1.14285 \times 10^{-2}$
Validity Range	H: 142-144.2 meters
Residual Error St. Dev.	0.01 cubic meters/KWH

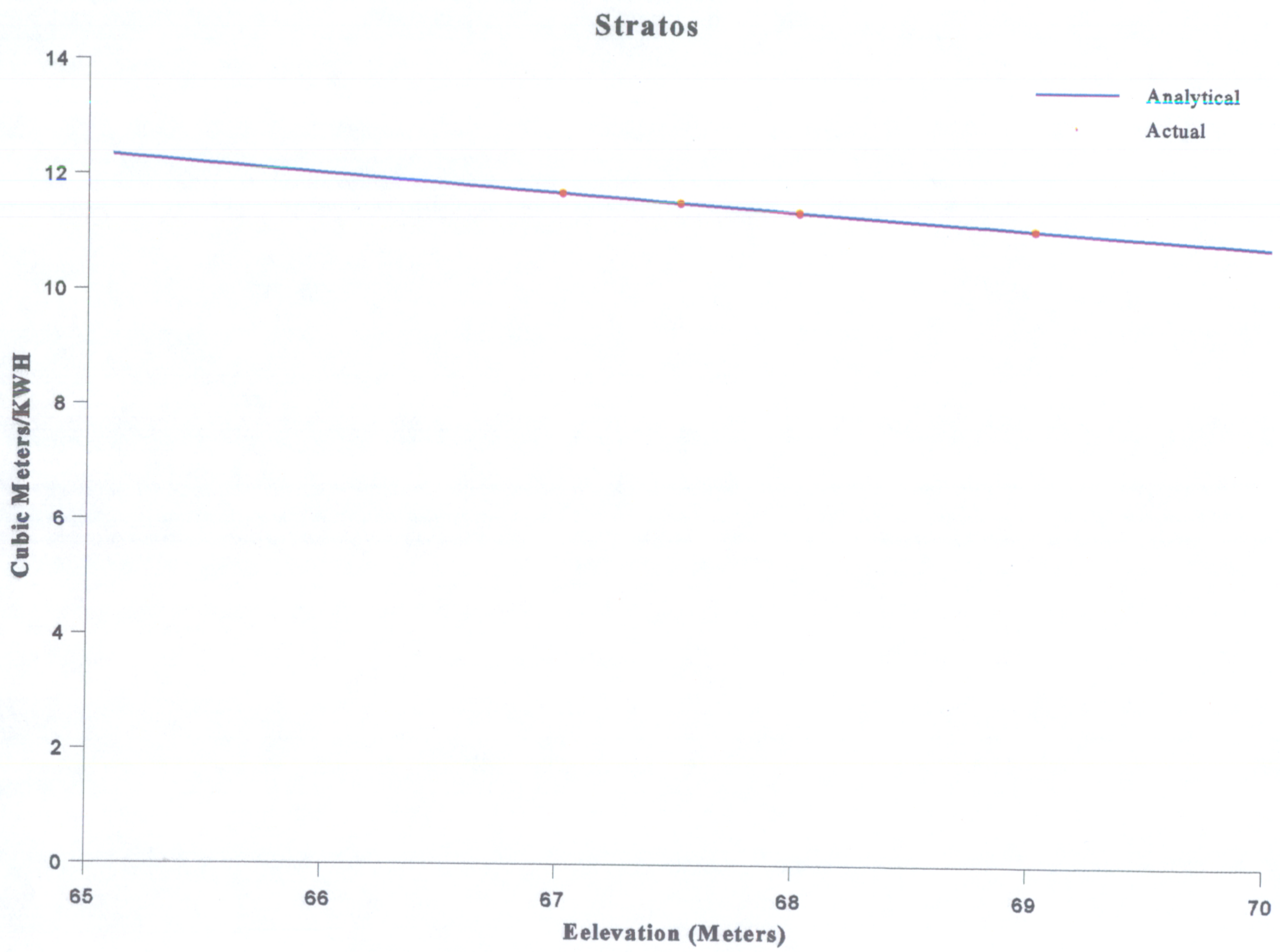

Figure A.3.3: Specific Generation Efficiency vs. Elevation Relationship for Stratos

APPENDIX B

FREQUENCY OF EXCEEDANCE RESULTS

Frequency of exceedance statistics Stratos discharge and system energy generation are calculated for both the base case (zero diversion) and the diversion scenario of 600 million cubic meters/year. The procedure to calculate the frequency of exceedance is as follows:

1. Rank the data from largest to smallest;
2. Estimate frequency of exceedance by

$$p = \frac{i - 0.4}{n + 0.2},$$

where i is the rank of the particular value and n is the total number of data (Helsel and Hirsch, "Statistical Methods In Water Resouces," Elsevier, 1992).

January

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Discharge (Million m^3/Month)	Diversion = 600 (Million m^3/year) Discharge (Million m^3/Month)
.936	145.720	186.900
.954	240.800	234.030
.941	259.610	236.330
.919	261.010	248.610
.896	275.130	254.620
.873	289.050	254.650
.851	307.040	256.480
.828	314.060	258.230
.805	316.170	275.500
.783	318.120	280.590
.760	341.740	284.850
.738	348.970	288.840
.715	360.400	289.310
.692	360.460	293.590
.670	360.630	295.950
.647	363.530	300.160
.624	381.230	302.660
.602	382.800	303.180
.579	383.390	305.720
.557	384.630	305.740
.534	388.740	306.480
.511	394.610	306.820
.489	398.090	307.920
.466	398.230	309.770
.443	399.190	318.260
.421	400.110	325.920
.398	400.810	327.610
.376	403.200	335.640
.353	405.100	344.940
.330	406.720	346.430
.308	413.730	358.480
.285	417.990	367.330
.262	421.820	372.270
.240	421.890	376.000
.217	422.310	376.750
.195	426.370	377.110
.172	430.560	379.030
.149	447.040	411.230
.127	470.630	417.310
.104	475.100	433.270
.081	485.290	436.930
.059	504.410	451.770
.036	507.270	465.180
.014	519.840	625.490

February

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Discharge (Million m^3/Month)	Diversion = 600 (Million m^3/year) Discharge (Million m^3/Month)
.986	91.960	160.880
.964	213.800	192.500
.941	213.960	200.040
.919	243.000	212.260
.896	277.940	256.030
.873	299.800	268.650
.851	315.160	271.660
.828	316.490	277.250
.805	320.610	277.590
.783	337.750	283.320
.760	341.530	288.080
.738	367.410	291.270
.715	373.840	291.710
.692	376.700	293.970
.670	377.630	297.580
.647	378.800	299.660
.624	379.710	301.470
.602	380.520	305.230
.579	383.120	307.520
.557	385.150	309.330
.534	390.390	309.900
.511	392.670	312.080
.489	393.680	313.470
.466	393.710	319.220
.443	400.670	321.320
.421	401.420	327.490
.398	403.020	329.950
.376	403.110	333.950
.353	405.330	335.530
.330	406.570	336.630
.308	408.340	338.340
.285	411.240	339.760
.262	411.590	351.660
.240	411.630	356.860
.217	429.060	358.270
.195	438.220	372.880
.172	445.360	421.950
.149	447.980	436.300
.127	461.600	460.700
.104	467.640	468.640
.081	509.440	509.930
.059	527.200	514.170
.036	582.130	529.760
.014	1279.020	1516.280

March

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Discharge (Million m^3/Month)	Diversion = 600 (Million m^3/year) Discharge (Million m^3/Month)
.986	157.410	157.410
.964	160.680	181.170
.941	209.920	196.890
.919	234.310	215.730
.896	239.650	216.110
.873	290.500	241.690
.851	294.460	249.520
.828	309.890	266.190
.805	319.940	266.880
.783	330.060	268.200
.760	341.140	273.410
.738	342.710	281.100
.715	348.700	281.350
.692	350.200	281.680
.670	351.070	281.700
.647	354.420	284.500
.624	355.640	289.570
.602	358.780	291.290
.579	360.100	291.670
.557	360.690	292.400
.534	363.740	293.590
.511	369.200	294.640
.489	369.570	295.810
.466	373.470	297.070
.443	378.990	297.090
.421	379.990	298.480
.398	381.170	313.520
.376	385.090	315.490
.353	385.330	315.610
.330	386.960	316.250
.308	387.780	320.850
.285	392.320	323.170
.262	392.980	327.450
.240	393.140	327.460
.217	393.310	328.320
.195	395.760	338.110
.172	406.920	371.990
.149	414.580	383.450
.127	431.850	426.080
.104	444.580	457.490
.081	454.720	481.260
.059	456.170	534.630
.036	487.830	739.640
.014	749.150	749.150

April

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Discharge (Million m^3/Month)	Diversion = 600 (Million m^3/year) Discharge (Million m^3/Month)
.986	147.550	133.450
.964	152.740	149.320
.941	158.250	185.000
.919	223.850	185.110
.896	232.580	203.800
.873	279.780	236.660
.851	292.960	241.150
.828	308.650	255.400
.805	310.340	258.390
.783	317.190	261.230
.760	328.250	271.200
.738	329.470	273.870
.715	338.060	276.240
.692	346.350	278.180
.670	346.860	280.410
.647	350.720	284.460
.624	355.020	288.960
.602	357.260	291.790
.579	358.270	292.750
.557	358.960	294.090
.534	358.970	296.350
.511	359.030	296.460
.489	359.330	297.020
.466	362.500	299.070
.443	367.930	299.270
.421	371.150	299.340
.398	371.220	304.030
.376	372.940	306.050
.353	373.960	307.870
.330	374.040	308.850
.308	374.100	310.160
.285	374.840	310.640
.262	375.140	316.750
.240	379.440	320.120
.217	381.610	324.120
.195	388.710	325.400
.172	389.520	337.330
.149	392.760	353.760
.127	392.950	418.520
.104	403.130	425.980
.081	405.590	436.910
.059	458.040	437.660
.036	465.640	443.000
.014	658.620	628.620

May

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Discharge (Million m^3/Month)	Diversion = 600 (Million m^3/year) Discharge (Million m^3/Month)
.986	133.860	145.150
.964	141.690	149.210
.941	177.700	159.390
.919	211.110	165.480
.896	223.310	189.180
.873	259.330	213.600
.851	263.550	228.430
.828	271.020	232.550
.805	272.910	235.010
.783	284.240	252.250
.760	290.780	258.880
.738	313.950	263.870
.715	336.050	264.740
.692	336.860	265.930
.670	337.760	268.880
.647	339.160	273.040
.624	339.370	275.260
.602	339.790	278.840
.579	343.290	280.420
.557	345.770	281.610
.534	347.850	282.000
.511	348.430	285.740
.489	350.810	286.210
.466	351.300	286.720
.443	351.340	290.030
.421	351.660	292.180
.398	353.340	292.490
.376	356.620	292.540
.353	362.300	296.140
.330	363.470	298.900
.308	363.630	306.170
.285	365.050	306.510
.262	365.680	306.650
.240	365.830	317.860
.217	368.880	319.200
.195	369.730	320.930
.172	373.590	322.270
.149	373.900	327.470
.127	375.330	332.660
.104	380.330	333.060
.081	382.230	339.450
.059	384.200	355.200
.036	394.830	360.440
.014	549.370	483.370

June

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Discharge (Million m^3/Month)	Diversion = 600 (Million m^3/year) Discharge (Million m^3/Month)
.986	57.810	.000
.964	138.060	151.040
.941	163.210	156.880
.919	209.040	158.240
.896	217.850	159.710
.873	235.880	201.010
.851	246.960	212.090
.828	257.860	213.870
.805	270.380	237.950
.783	284.830	251.990
.760	303.090	252.190
.738	315.720	252.950
.715	327.170	253.130
.692	328.930	255.820
.670	329.170	259.040
.647	330.240	260.630
.624	330.560	260.650
.602	332.880	261.570
.579	334.380	263.810
.557	335.190	264.560
.534	336.540	268.380
.511	339.090	271.250
.489	339.490	272.940
.466	339.510	276.590
.443	341.520	280.450
.421	342.590	281.530
.398	342.980	281.910
.376	343.490	281.920
.353	344.070	283.630
.330	346.000	283.820
.308	346.130	284.780
.285	347.060	285.530
.262	349.190	288.910
.240	352.150	292.780
.217	352.290	293.950
.195	354.320	294.490
.172	355.180	298.540
.149	356.620	300.550
.127	357.200	307.060
.104	357.570	313.830
.081	360.460	314.570
.059	366.440	316.430
.036	367.910	317.410
.014	377.260	357.650

July

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Discharge (Million m^3/Month)	Diversion = 600 (Million m^3/year) Discharge (Million m^3/Month)
.986	16.670	.000
.964	144.910	34.790
.941	185.980	154.650
.919	204.790	156.560
.896	218.560	165.370
.873	223.590	191.900
.851	233.960	201.020
.828	250.740	205.540
.805	272.230	242.450
.783	287.180	247.140
.760	297.980	257.010
.738	299.190	258.080
.715	331.830	258.970
.692	333.030	259.870
.670	333.870	260.390
.647	334.350	260.850
.624	334.460	265.110
.602	334.630	268.160
.579	335.910	271.510
.557	336.440	271.900
.534	336.490	273.460
.511	337.900	274.770
.489	339.210	277.120
.466	339.340	279.000
.443	340.010	282.330
.421	340.360	285.080
.398	340.470	285.400
.376	341.510	285.700
.353	345.760	286.520
.330	347.570	288.810
.308	347.870	290.500
.285	349.420	291.820
.262	350.120	292.470
.240	353.990	293.180
.217	354.470	297.410
.195	354.730	301.810
.172	354.770	301.940
.149	354.900	302.540
.127	355.030	306.220
.104	355.430	310.810
.081	359.840	324.920
.059	363.620	327.010
.036	368.130	329.690
.014	372.390	333.340

August

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Discharge (Million m^3/Month)	Diversion = 600 (Million m^3/year) Discharge (Million m^3/Month)
.986	18.300	.000
.964	145.640	.000
.941	159.530	35.880
.919	179.260	156.550
.896	204.770	164.440
.873	209.410	178.240
.851	225.890	193.590
.828	244.420	199.670
.805	263.490	241.720
.783	271.900	259.320
.760	288.930	260.510
.738	291.990	261.650
.715	309.190	261.820
.692	319.830	266.090
.670	319.850	267.440
.647	333.120	267.580
.624	335.120	273.470
.602	336.020	274.710
.579	336.320	275.140
.557	337.700	275.950
.534	338.120	277.310
.511	338.160	281.520
.489	339.150	283.750
.466	339.960	285.680
.443	342.550	286.070
.421	344.010	286.670
.398	344.100	288.500
.376	345.070	290.600
.353	345.600	290.670
.330	348.830	291.170
.308	350.840	292.770
.285	351.170	298.280
.262	352.820	299.230
.240	354.850	302.230
.217	357.940	308.890
.195	358.950	310.700
.172	361.830	315.070
.149	367.460	316.660
.127	368.520	322.970
.104	372.560	327.970
.081	372.890	336.100
.059	375.740	338.150
.036	377.080	339.950
.014	378.490	354.510

September

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Discharge (Million m^3/Month)	Diversion = 600 (Million m^3/year) Discharge (Million m^3/Month)
.986	17.590	.000
.964	31.800	.000
.941	185.680	.000
.919	192.250	132.980
.896	203.740	170.800
.873	227.580	194.840
.851	235.450	201.370
.828	244.690	212.900
.805	267.840	232.200
.783	286.660	240.510
.760	301.220	245.060
.738	307.450	255.470
.715	314.970	256.450
.692	320.710	277.620
.670	320.790	278.390
.647	321.180	278.990
.624	321.350	280.490
.602	325.080	281.360
.579	340.280	288.960
.557	348.640	289.400
.534	350.850	297.120
.511	352.110	298.880
.489	352.360	302.090
.466	353.710	304.050
.443	354.120	306.440
.421	356.090	310.470
.398	357.250	313.220
.376	358.660	313.380
.353	358.810	314.370
.330	360.190	317.550
.308	360.570	318.720
.285	362.400	321.810
.262	362.940	322.200
.240	364.890	323.450
.217	369.540	327.520
.195	370.410	333.120
.172	372.490	333.270
.149	374.040	333.820
.127	375.160	334.240
.104	375.540	335.690
.081	384.830	363.040
.059	393.550	365.130
.036	393.740	367.000
.014	403.600	383.470

October

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Discharge (Million m^3/Month)	Diversion = 600 (Million m^3/year) Discharge (Million m^3/Month)
.986	48.450	.000
.964	106.090	.000
.941	178.590	.000
.919	197.180	128.460
.896	201.010	144.020
.873	208.720	190.000
.851	210.280	196.790
.828	269.180	235.440
.805	276.890	239.300
.783	287.280	262.840
.760	323.670	274.420
.738	323.990	275.110
.715	326.920	280.190
.692	329.130	287.720
.670	334.620	290.470
.647	339.780	293.020
.624	341.090	294.990
.602	351.220	297.090
.579	357.820	297.250
.557	360.200	309.670
.534	363.670	312.830
.511	364.260	316.720
.489	367.050	316.760
.466	367.360	317.470
.443	367.610	319.530
.421	370.370	321.730
.398	373.210	324.970
.376	374.940	325.400
.353	375.830	328.490
.330	376.460	332.080
.308	376.810	338.280
.285	378.680	341.600
.262	382.640	342.510
.240	384.510	344.010
.217	385.200	344.080
.195	385.680	348.000
.172	390.730	349.060
.149	391.470	352.830
.127	392.370	353.900
.104	410.510	361.550
.081	412.230	380.200
.059	413.320	382.770
.036	420.600	387.320
.014	423.160	415.380

November

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Discharge (Million m^3/Month)	Diversion = 600 (Million m^3/year) Discharge (Million m^3/Month)
.986	185.180	.000
.964	198.070	.000
.941	206.410	18.660
.919	207.590	154.940
.896	229.800	186.840
.873	249.890	192.730
.851	263.360	199.880
.828	304.250	235.350
.805	333.210	257.220
.783	337.290	257.320
.760	351.650	265.390
.738	352.580	270.230
.715	357.180	275.290
.692	361.070	287.020
.670	365.370	297.650
.647	365.910	303.140
.624	372.260	316.340
.602	379.130	316.870
.579	383.230	317.300
.557	385.760	325.800
.534	391.580	339.200
.511	394.690	346.230
.489	396.590	347.310
.466	400.320	348.980
.443	400.820	349.890
.421	401.570	351.180
.398	402.340	357.950
.376	402.690	360.380
.353	404.030	364.890
.330	405.090	367.480
.308	405.820	369.440
.285	406.100	370.800
.262	408.940	371.370
.240	411.270	375.320
.217	413.860	377.270
.195	415.220	378.920
.172	415.760	386.230
.149	420.170	395.230
.127	421.570	397.790
.104	442.320	401.290
.081	455.090	410.080
.059	457.700	411.290
.036	475.840	422.000
.014	504.570	447.600

December

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Discharge (Million m^3/Month)	Diversion = 600 (Million m^3/year) Discharge (Million m^3/Month)
.986	239.640	147.080
.964	247.030	206.190
.941	257.830	221.190
.919	265.920	239.120
.896	277.020	240.660
.873	307.700	265.940
.851	308.640	269.000
.828	309.550	270.560
.805	311.410	272.300
.783	334.550	292.330
.760	349.840	293.880
.738	354.410	301.530
.715	359.360	311.360
.692	367.960	312.470
.670	368.770	313.890
.647	375.580	314.100
.624	378.100	318.110
.602	385.160	322.180
.579	390.800	322.320
.557	391.790	324.010
.534	400.930	326.290
.511	407.980	333.410
.489	408.330	339.120
.466	409.630	347.990
.443	409.980	353.950
.421	412.070	357.480
.398	412.490	362.750
.376	412.740	364.410
.353	413.950	373.490
.330	419.300	374.640
.308	423.460	378.140
.285	429.490	380.220
.262	431.510	384.600
.240	443.020	391.490
.217	446.370	395.530
.195	451.170	396.270
.172	456.450	397.310
.149	464.910	398.600
.127	471.090	402.380
.104	472.000	411.240
.081	472.650	432.810
.059	486.340	455.230
.036	508.170	464.030
.014	518.420	472.500

January

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Energy (GWH/Month)	Diversion = 600 (Million m^3/year) Energy (GWH/Month)
.986	61.419	80.020
.964	90.008	92.959
.941	108.853	103.208
.919	110.725	104.674
.896	114.162	105.808
.873	124.810	109.456
.851	127.797	110.089
.828	129.075	113.701
.805	130.421	114.537
.783	130.818	121.860
.760	148.166	122.376
.738	150.773	124.268
.715	153.932	127.376
.692	161.468	128.622
.670	161.565	137.245
.647	167.676	138.477
.624	170.623	139.191
.602	172.785	139.745
.579	182.646	139.827
.557	187.061	140.531
.534	189.121	140.536
.511	189.133	140.599
.489	189.342	140.657
.466	189.351	140.910
.443	189.362	140.978
.421	189.841	141.259
.398	189.965	141.311
.376	189.977	141.407
.353	190.012	145.408
.330	190.234	155.103
.308	190.858	158.969
.285	191.357	172.083
.262	194.128	177.123
.240	196.468	177.132
.217	200.046	180.354
.195	203.764	182.516
.172	208.312	184.059
.149	213.317	188.259
.127	226.128	193.074
.104	239.253	193.513
.081	242.741	207.146
.059	243.214	211.593
.036	245.271	240.065
.014	256.312	315.222

Februayr

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Energy (GWH/Month)	Diversion = 600 (Million m^3/year) Energy (GWH/Month)
.986	35.171	65.478
.964	88.784	83.172
.941	91.623	83.389
.919	100.712	87.938
.896	113.136	106.405
.873	122.200	107.573
.851	124.121	113.480
.828	130.298	113.815
.805	134.621	115.938
.783	145.858	116.855
.760	147.057	125.155
.738	151.142	127.196
.715	160.436	131.474
.692	161.447	136.927
.670	173.689	138.755
.647	173.911	139.346
.624	175.902	139.976
.602	178.585	140.215
.579	185.100	140.285
.557	186.140	140.388
.534	187.233	140.472
.511	188.988	141.077
.489	189.092	141.130
.466	189.244	141.494
.443	189.348	141.708
.421	189.406	141.965
.398	189.656	143.312
.376	189.702	143.915
.353	189.770	144.237
.330	190.371	144.501
.308	191.765	147.354
.285	192.435	155.104
.262	192.671	161.377
.240	193.398	162.951
.217	195.263	168.310
.195	195.556	169.979
.172	214.147	205.825
.149	214.354	222.481
.127	232.637	227.466
.104	233.727	259.381
.081	254.106	263.467
.059	296.785	294.836
.036	304.777	297.092
.014	651.495	665.400

March

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Energy (GWH/Month)	Diversion = 600 (Million m^3/year) Energy (GWH/Month)
.986	65.345	65.345
.964	68.515	73.364
.941	84.586	85.049
.919	96.581	86.576
.896	102.697	96.411
.873	131.278	110.705
.851	131.552	111.377
.828	135.533	118.569
.805	140.561	121.735
.783	150.232	125.604
.760	150.260	135.678
.738	151.298	136.497
.715	159.569	137.738
.692	166.730	138.571
.670	179.094	139.872
.647	179.223	139.906
.624	185.189	140.094
.602	186.419	140.199
.579	187.011	140.212
.557	187.012	140.309
.534	187.787	140.525
.511	188.324	140.668
.489	189.277	140.699
.466	189.485	141.238
.443	189.557	141.386
.421	189.613	143.602
.398	189.687	146.469
.376	189.720	146.753
.353	189.770	147.953
.330	189.874	153.301
.308	190.128	153.404
.285	190.230	156.783
.262	191.181	157.203
.240	191.318	158.733
.217	191.459	163.305
.195	195.976	168.351
.172	197.049	184.944
.149	204.819	189.457
.127	217.229	229.534
.104	225.310	264.349
.081	244.849	269.587
.059	249.429	313.865
.036	277.270	441.416
.014	441.416	447.174

April

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Energy (GWH/Month)	Diversion = 600 (Million m^3/year) Energy (GWH/Month)
.986	56.530	54.470
.964	63.572	58.431
.941	64.043	75.994
.919	93.547	79.673
.896	101.242	89.954
.873	130.052	109.382
.851	136.352	111.661
.828	137.299	124.037
.805	139.232	129.202
.783	151.281	130.613
.760	152.263	133.352
.738	156.861	137.243
.715	161.378	138.881
.692	175.605	139.200
.670	175.957	139.538
.647	184.482	140.178
.624	186.387	140.218
.602	186.739	140.575
.579	187.520	140.706
.557	187.771	144.909
.534	188.160	146.036
.511	189.584	146.338
.489	189.611	147.817
.466	189.649	151.492
.443	189.652	151.719
.421	189.883	151.810
.398	190.032	155.060
.376	190.258	156.159
.353	190.501	163.998
.330	190.518	164.119
.308	191.613	164.866
.285	191.765	165.740
.262	192.263	165.823
.240	193.213	166.015
.217	195.746	166.881
.195	199.155	167.003
.172	199.197	168.679
.149	209.990	208.400
.127	216.847	249.896
.104	221.401	253.400
.081	240.762	263.655
.059	283.395	266.673
.036	286.298	271.245
.014	394.119	374.813

May

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Energy (GWH/Month)	Diversion = 600 (Million m^3/year) Energy (GWH/Month)
.986	56.193	61.928
.964	60.128	62.526
.941	76.762	74.258
.919	98.660	77.264
.896	98.992	88.175
.873	132.273	105.966
.851	132.923	112.139
.828	133.486	119.083
.805	135.105	119.605
.783	140.070	133.424
.760	149.131	139.745
.738	159.389	139.949
.715	178.868	139.975
.692	182.914	140.063
.670	186.294	140.514
.647	186.928	140.566
.624	188.488	140.745
.602	189.474	142.450
.579	189.486	148.211
.557	189.586	151.546
.534	189.613	152.305
.511	189.740	153.267
.489	189.797	156.706
.466	189.993	159.170
.443	190.142	159.396
.421	190.187	164.898
.398	190.495	165.106
.376	191.292	165.481
.353	191.643	165.562
.330	192.369	165.663
.308	192.788	165.701
.285	193.508	165.764
.262	193.858	166.205
.240	194.484	166.632
.217	199.725	166.701
.195	206.489	179.778
.172	209.886	180.157
.149	210.152	180.606
.127	214.499	185.315
.104	219.154	187.587
.081	219.841	192.187
.059	220.131	196.249
.036	229.336	200.964
.014	331.925	289.451

June

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Energy (GWH/Month)	Diversion = 600 (Million m^3/year) Energy (GWH/Month)
.986	26.756	1.235
.964	64.941	72.144
.941	79.262	76.301
.919	99.840	78.134
.896	100.193	83.071
.873	119.735	106.478
.851	122.328	108.816
.828	129.836	109.033
.805	140.715	122.156
.783	143.039	134.501
.760	155.149	139.217
.738	157.088	139.972
.715	177.240	140.145
.692	183.213	140.415
.670	184.130	140.508
.647	189.201	140.605
.624	189.349	140.619
.602	189.416	141.079
.579	189.583	144.843
.557	189.620	148.429
.534	189.692	149.524
.511	189.723	153.108
.489	189.825	153.725
.466	190.247	156.814
.443	190.385	160.471
.421	190.528	160.953
.398	190.852	161.859
.376	191.049	162.076
.353	191.658	163.558
.330	192.320	163.799
.308	192.816	164.398
.285	193.909	165.270
.262	195.659	166.348
.240	197.250	168.273
.217	204.756	168.449
.195	207.502	168.571
.172	210.009	181.706
.149	211.847	182.846
.127	212.155	183.612
.104	213.281	186.427
.081	213.429	188.270
.059	215.581	189.823
.036	219.381	190.926
.014	220.316	197.882

July

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Energy (GWH/Month)	Diversion = 600 (Million m^3/year) Energy (GWH/Month)
.986	8.480	.000
.964	67.456	10.179
.941	86.030	72.738
.919	97.759	75.832
.896	100.092	79.820
.873	108.794	96.435
.851	114.141	101.098
.828	123.345	102.753
.805	136.036	122.676
.783	143.683	133.530
.760	151.741	138.025
.738	152.021	139.573
.715	171.523	139.960
.692	178.628	140.331
.670	178.629	140.361
.647	188.889	140.367
.624	188.922	140.478
.602	189.240	140.766
.579	189.519	141.540
.557	189.595	150.344
.534	189.664	151.210
.511	189.672	152.925
.489	189.728	153.462
.466	190.111	159.915
.443	190.534	162.544
.421	190.657	162.641
.398	190.719	164.963
.376	190.909	165.030
.353	190.947	166.564
.330	191.100	168.407
.308	191.507	168.656
.285	195.273	170.215
.262	200.534	170.255
.240	201.311	170.882
.217	202.492	171.522
.195	207.015	175.637
.172	207.614	181.514
.149	210.234	182.896
.127	213.052	183.371
.104	213.190	183.712
.081	214.451	192.373
.059	218.228	195.388
.036	221.409	195.638
.014	221.626	199.757

August

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Energy (GWH/Month)	Diversion = 600 (Million m^3/year) Energy (GWH/Month)
.986	9.232	.000
.964	68.515	.000
.941	72.494	.000
.919	84.347	52.169
.896	98.086	75.566
.873	101.525	86.415
.851	107.862	91.434
.828	118.897	95.791
.805	131.467	108.616
.783	138.872	116.251
.760	144.910	120.163
.738	147.470	122.374
.715	159.649	124.064
.692	165.343	140.045
.670	166.803	140.147
.647	176.651	140.323
.624	177.004	140.478
.602	178.512	140.930
.579	189.351	149.709
.557	189.545	150.360
.534	189.594	154.629
.511	189.629	156.527
.489	189.677	158.616
.466	190.005	158.886
.443	190.214	159.940
.421	190.295	166.436
.398	190.494	166.884
.376	190.585	170.611
.353	190.637	171.782
.330	191.148	172.375
.308	192.501	174.153
.285	195.445	174.879
.262	200.048	175.463
.240	203.376	175.748
.217	207.936	177.085
.195	208.255	178.513
.172	208.273	179.182
.149	209.915	181.683
.127	214.793	182.339
.104	216.473	182.849
.081	221.683	198.917
.059	222.465	201.083
.036	223.530	201.147
.014	224.328	213.559

September

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Energy (GWH/Month)	Diversion = 600 (Million m^3/year) Energy (GWH/Month)
.986	8.789	.000
.964	13.707	.000
.941	82.950	.000
.919	92.292	52.169
.896	97.424	75.566
.873	103.390	86.415
.851	109.117	91.434
.828	113.475	95.791
.805	129.211	108.616
.783	137.105	116.251
.760	142.253	120.163
.738	147.099	122.374
.715	156.427	124.064
.692	158.396	140.045
.670	158.698	140.147
.647	162.071	140.323
.624	162.990	140.478
.602	164.742	140.930
.579	174.903	149.709
.557	189.305	150.360
.534	189.360	154.629
.511	189.558	156.527
.489	189.606	158.616
.466	189.963	158.886
.443	190.117	159.940
.421	190.138	166.436
.398	190.138	166.884
.376	190.538	170.611
.353	190.623	171.782
.330	192.267	172.375
.308	194.671	174.153
.285	196.189	174.879
.262	200.073	175.463
.240	200.796	175.748
.217	206.392	177.085
.195	206.919	178.513
.172	208.007	179.182
.149	209.543	181.683
.127	211.609	182.339
.104	216.771	182.849
.081	218.621	198.917
.059	222.455	201.083
.036	223.268	201.147
.014	230.387	213.559

October

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Energy (GWH/Month)	Diversion = 600 (Million m^3/year) Energy (GWH/Month)
.986	21.166	.000
.964	43.796	.000
.941	69.136	.797
.919	84.098	60.895
.896	86.851	62.156
.873	92.319	77.515
.851	93.629	84.236
.828	122.498	109.505
.805	127.081	110.737
.783	132.226	117.060
.760	153.372	121.209
.738	154.775	131.364
.715	157.574	132.236
.692	157.977	134.169
.670	158.412	140.089
.647	158.585	140.115
.624	161.124	140.919
.602	164.840	148.595
.579	178.981	149.383
.557	179.125	153.621
.534	186.471	157.100
.511	189.389	157.662
.489	189.874	158.130
.466	189.888	160.205
.443	190.088	162.223
.421	190.318	166.694
.398	190.376	167.633
.376	190.395	169.430
.353	197.076	170.481
.330	197.171	174.566
.308	197.611	175.229
.285	198.561	175.428
.262	200.802	176.122
.240	201.926	179.425
.217	205.972	180.409
.195	206.396	180.595
.172	207.126	181.102
.149	209.626	183.150
.127	211.463	183.768
.104	220.917	184.515
.081	223.454	201.387
.059	223.503	201.966
.036	230.719	202.768
.014	235.646	222.528

November

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Energy (GWH/Month)	Diversion = 600 (Million m^3/year) Energy (GWH/Month)
.986	72.974	4.543
.964	76.327	4.662
.941	76.685	9.360
.919	80.968	58.202
.896	86.219	66.763
.873	90.791	67.361
.851	98.767	69.910
.828	132.079	92.321
.805	132.273	104.785
.783	138.943	106.052
.760	143.053	106.458
.738	147.324	117.262
.715	153.869	124.442
.692	157.234	126.685
.670	158.887	135.731
.647	159.598	136.755
.624	170.644	147.749
.602	172.478	148.998
.579	183.398	151.175
.557	183.830	153.472
.534	185.868	158.321
.511	186.698	160.487
.489	188.217	163.281
.466	189.277	164.397
.443	189.306	167.820
.421	189.363	168.597
.398	189.653	171.623
.376	189.828	173.037
.353	190.274	173.769
.330	197.786	176.296
.308	197.899	176.932
.285	200.634	176.976
.262	202.367	178.016
.240	204.125	178.135
.217	204.932	179.723
.195	205.233	184.202
.172	207.309	185.952
.149	207.510	187.440
.127	213.845	190.540
.104	216.461	190.568
.081	221.992	193.043
.059	223.313	193.366
.036	231.600	201.501
.014	239.199	223.638

December

Frequency of Exceedance	Diversion = 0 (Million m^3/year) Energy (GWH/Month)	Diversion = 600 (Million m^3/year) Energy (GWH/Month)
.986	86.819	36.604
.964	89.316	78.546
.941	96.413	92.412
.919	105.872	96.275
.896	117.638	100.522
.873	120.291	103.666
.851	121.368	104.408
.828	126.091	105.707
.805	133.238	113.387
.783	133.274	116.429
.760	149.072	120.574
.738	153.272	125.240
.715	153.671	132.964
.692	154.162	134.170
.670	156.834	137.473
.647	156.906	138.784
.624	171.222	139.616
.602	173.928	139.990
.579	178.848	140.478
.557	182.047	140.800
.534	185.215	140.878
.511	187.501	141.107
.489	187.738	141.585
.466	189.346	143.111
.443	189.402	155.945
.421	189.410	157.069
.398	189.501	164.217
.376	189.727	165.293
.353	189.831	167.642
.330	190.151	170.529
.308	190.684	171.669
.285	190.922	174.593
.262	192.548	176.357
.240	197.715	177.188
.217	204.396	179.684
.195	205.887	182.380
.172	207.699	185.600
.149	211.320	186.031
.127	214.689	189.106
.104	227.651	192.609
.081	228.110	194.186
.059	230.690	204.507
.036	243.116	204.722
.014	244.269	207.964