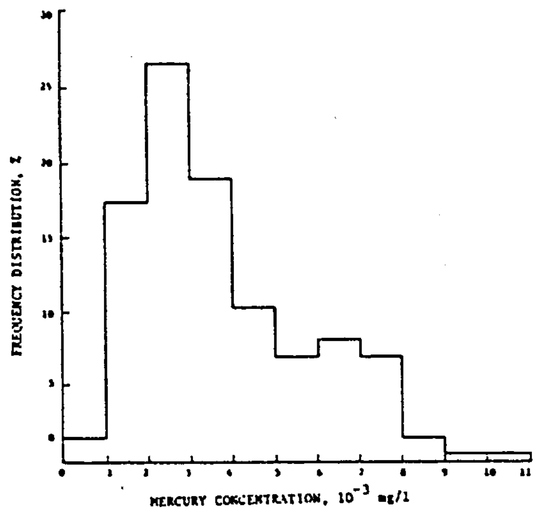

Figure 5.9a Frequency distribution of effluent chloride ion daily discharge at plant 144.

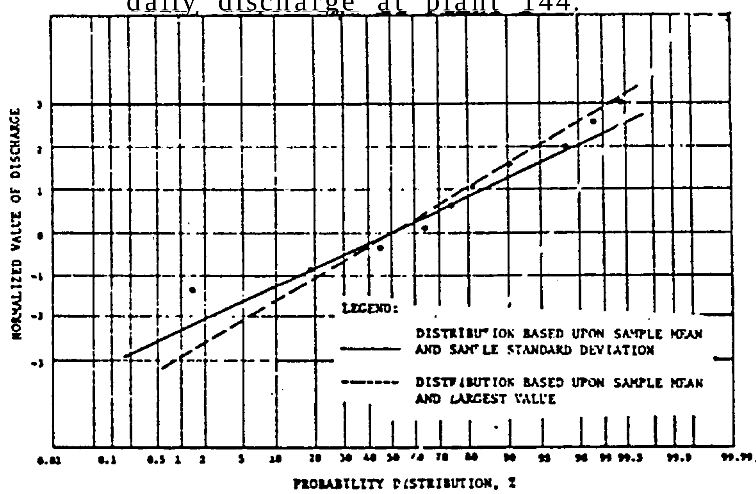

Figure 5.9b Normal.

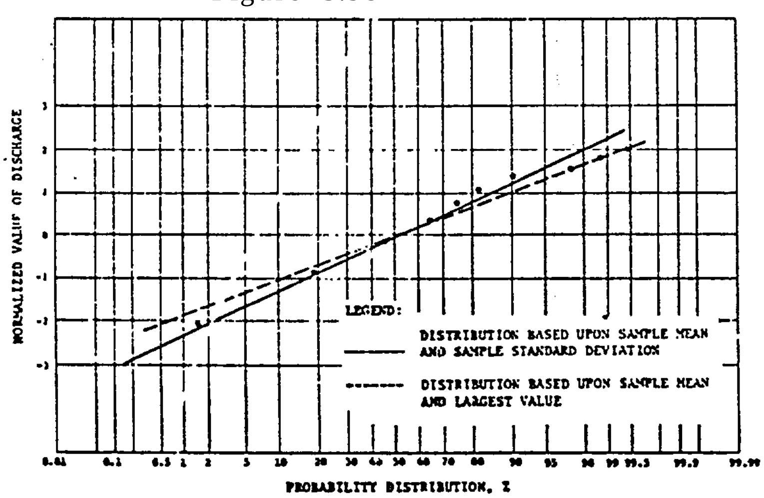

Figure 5.9c Lognormal.

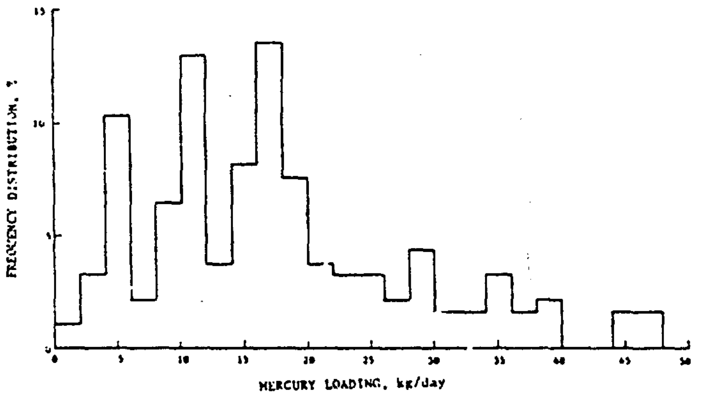

Figure 5.10a Frequency distribution of effluent mercury daily discharge at plant 144.

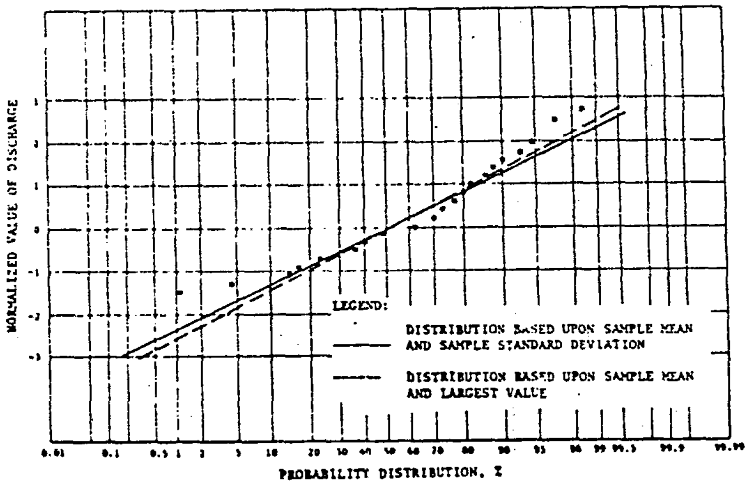

Figure 5.10b Normal.

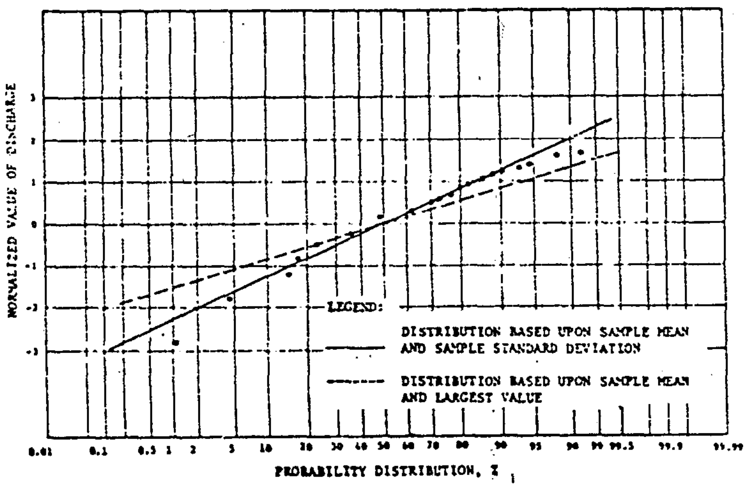

Figure 5.10c Lognormal.

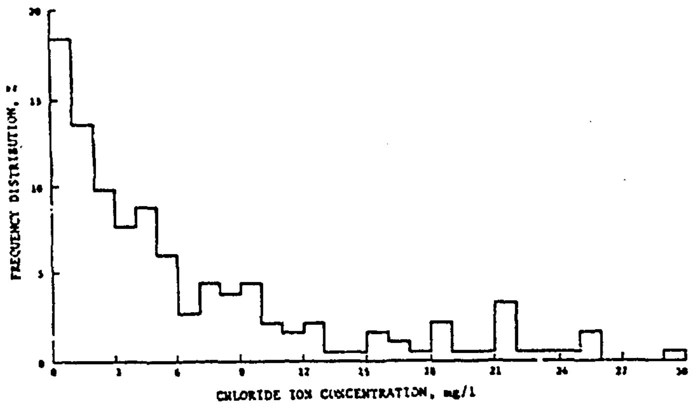

Figure 5.11a Frequency distribution of effluent chloride ion concentration at plant 144.

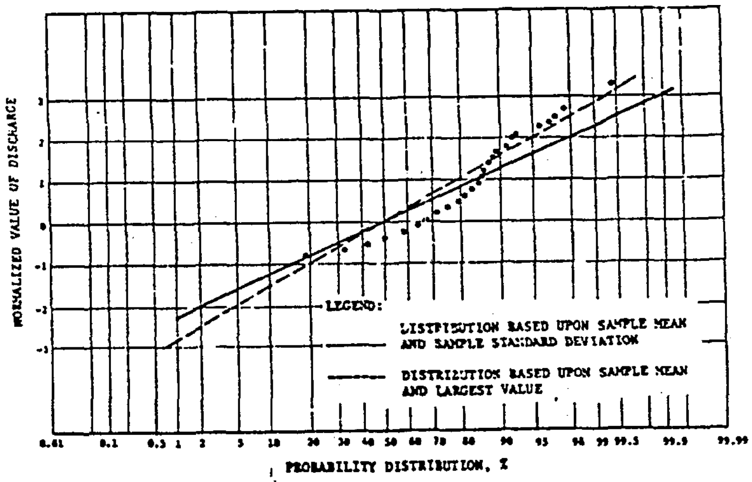

Figure 5.11b Normal.

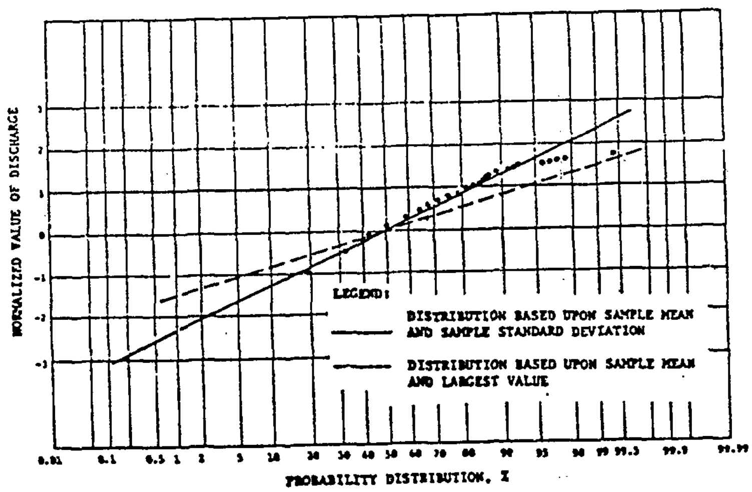

Figure 5.11c Lognormal.

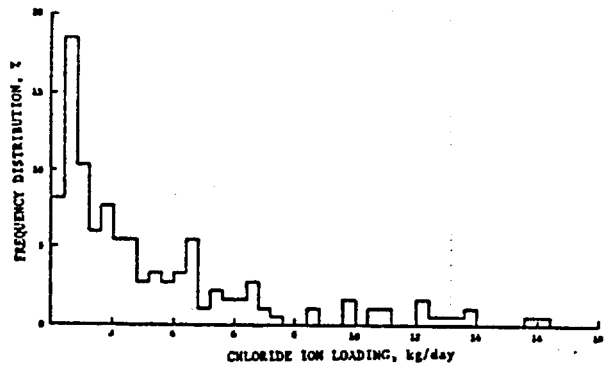

Figure 5.12a Frequency distribution of effluent chloride ion daily discharge at plant 144.

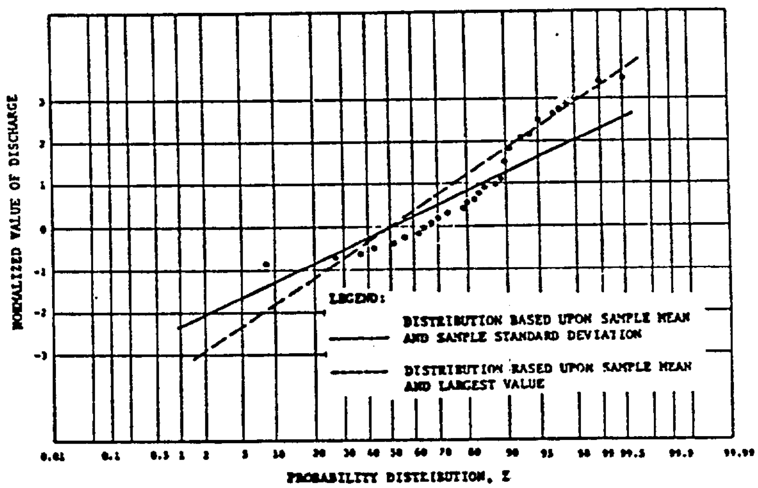

Figure 5.12b Normal.

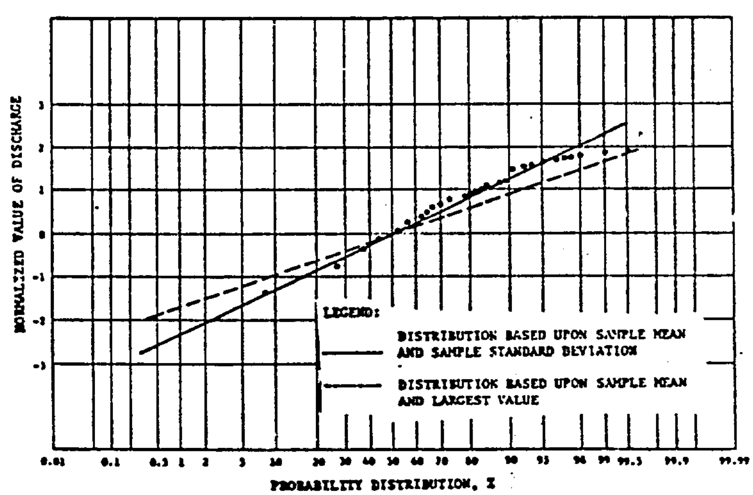

Figure 5.12c Lognormal.

Effect of Seasonal Variations on Distribution

Next an investigation of distribution properties of effluent pollutants, with emphasis on the possible effect of seasonality, is presented. The data used in this study were obtained from the Palo Alto Municipal Waste Treatment Plant [4].

A plot of the empirical distribution of the samples of BOD loadings from a dry month (July 1973) is presented in Figure 5.13. For convenience, they have been normalized, that is, their mean is zero and standard deviation is unity. The solid line represents the standard normal distribution and it appears (visually) to fit well. The normal distribution, using an estimate of the standard deviation from the maximum observed value (see Appendix A for the estimation procedure), is plotted with a broken line. The maximum likelihood estimate $\hat{\sigma}$ based on the largest observation (1.88 in this case) is

$$\hat{\sigma} = \frac{1.88}{\zeta} = \frac{1.88}{2.01} = 0.935$$

where the value of ζ was obtained from Figure A.1.1 of Appendix A, corresponding to the number of measurements n = 29. The two distributions are almost identical, and this illustrates the effectiveness of the estimation procedure developed in Appendix A.

The plot of the logs of the BOD loadings from the same dry month, also normalized as before appears in Figure 5.14. The fit to a normal distribution in the figure, which corresponds to the loadings being lognormally distributed, is not as good as in Figure 5.13; however, as discussed earlier, it is acceptable according to the Kolmogorov-Smirnov test. The broken line corresponds to the distribution with the standard deviation estimated according to the same method as above.

Plots of daily samples of BOD loadings for a wet month (November 1973) are given in Figures 5.15 and 5.16 under the normal and lognormal

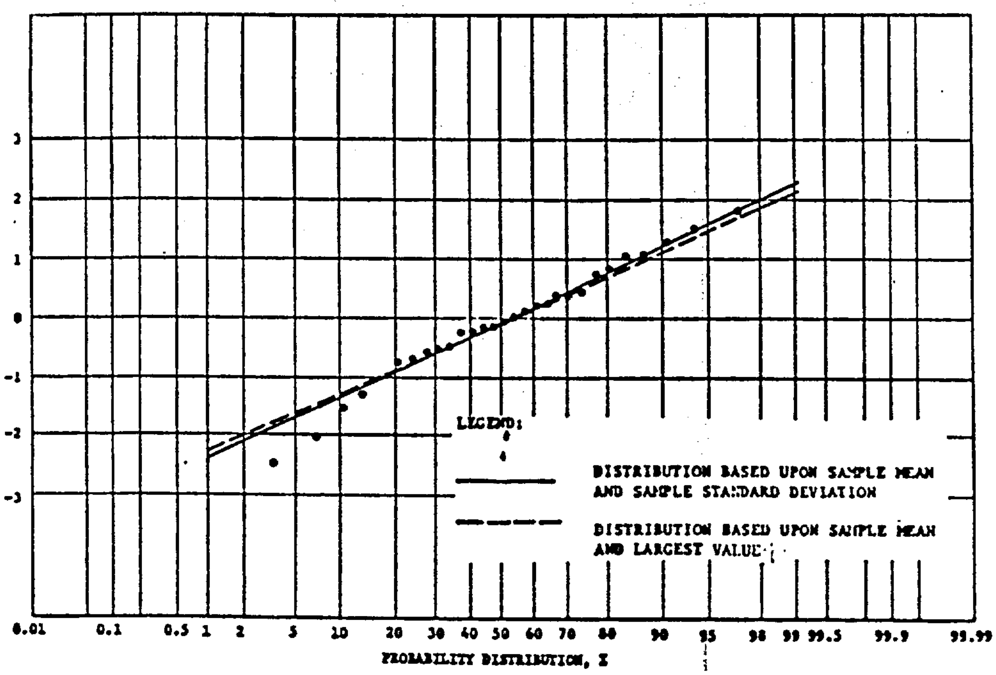

Figure 5.13 Daily samples of BOD loadings from a dry month (normal assumption).

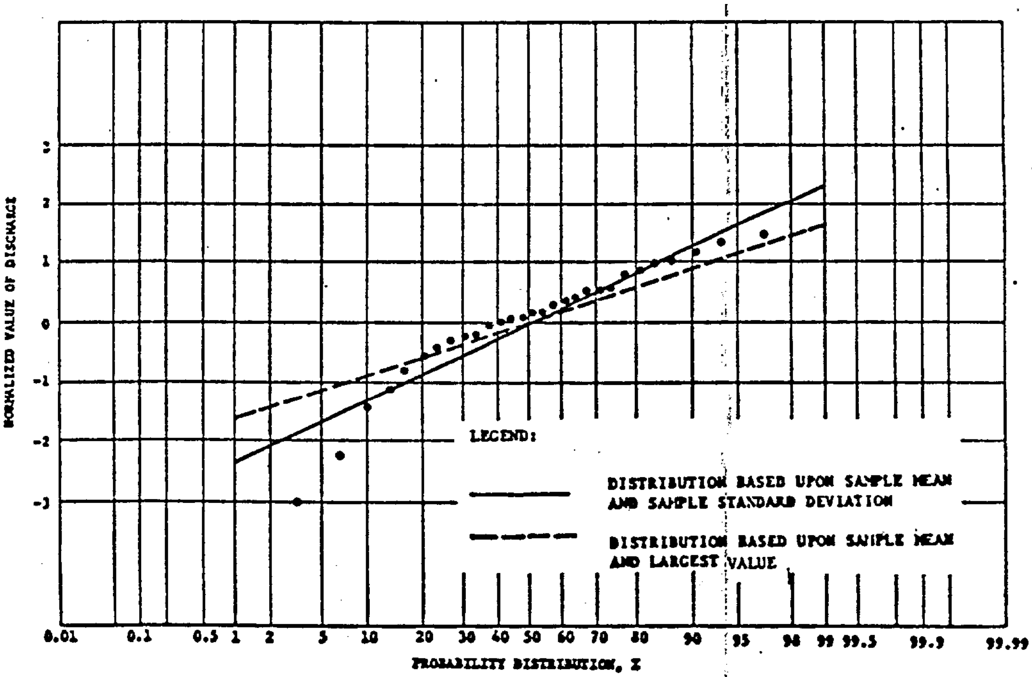

Figure 5.14 Daily samples of BOD from a dry month (lognormal assumption).

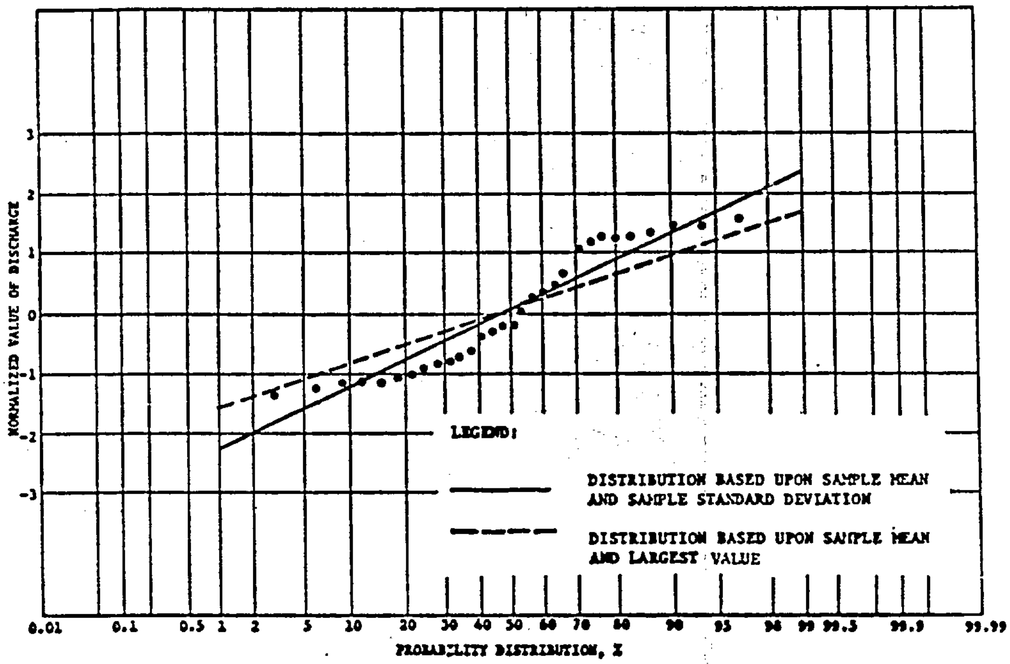

Figure 5.15 Daily samples of BOD loadings from a wet month (normal assumption).

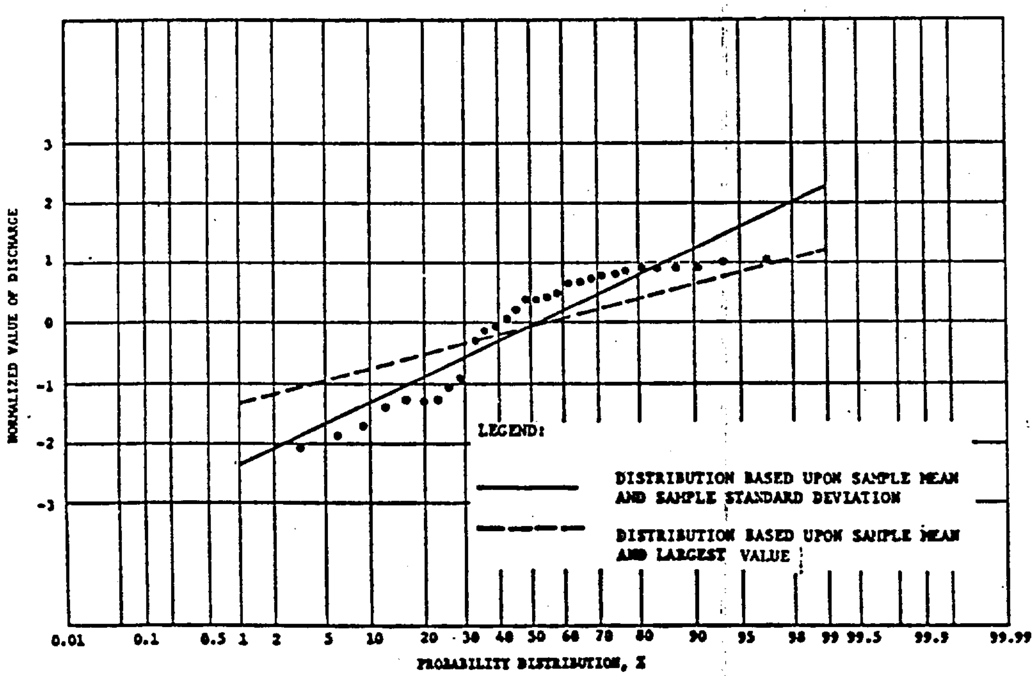

Figure 5.16 Daily samples of BOD loadings from a wet month (lognormal assumption).

assumptions, respectively. While both these assumptions are acceptable, the tail-fit of the distributions that use the maximum likelihood estimate of σ based upon the largest observation (dashed line) is better.

The dry month samples exhibit a more regular behavior than the wet month samples -- the straight line fit is better for the former. Nevertheless the BOD data from both seasons can be accepted as either normal or lognormal. Thus it can be seen that the distributional properties of the BOD samples from a wet month are similar to those from a dry month.

Measurements of suspended solids (dry and wet month) are plotted in Figures 5.17 - 5.18 under the normal and lognormal assumption. A more irregular behavior is observed again during a wet month but the normal or lognormal distribution is still acceptable to describe the variability regardless of season.

A set of 28 coliform measurements (January 1974) are plotted in Figure 5.21 under the lognormal assumption, and again, a good fit is observed in the upper tail. This set of data was accepted at 15% significance level as lognormal, but rejected even at α = 1% as being normal.

The distribution studies performed on the main constituents of a waste treatment plant, (BOD, SS) show that both the normal and the lognormal assumptions can be accepted at a high level of significance. The distribution estimation method based upon monthly mean and monthly maximum developed in Appendix A has been illustrated and shown to give very good fit for the tail of the distribution. A study on coliform data showed that it is best modeled by a lognormal model. From the seasonality study it appears that there can be noticeable changes from season to season of a constituent's statistical description. For the purpose of obtaining the expected damage and the probability of violation the "adaptive" feature of the Bayesian updating method described in Section V.2 becomes important. This property of the updating procedure will ensure acceptable performance of the priority procedure despite the seasonal variability.

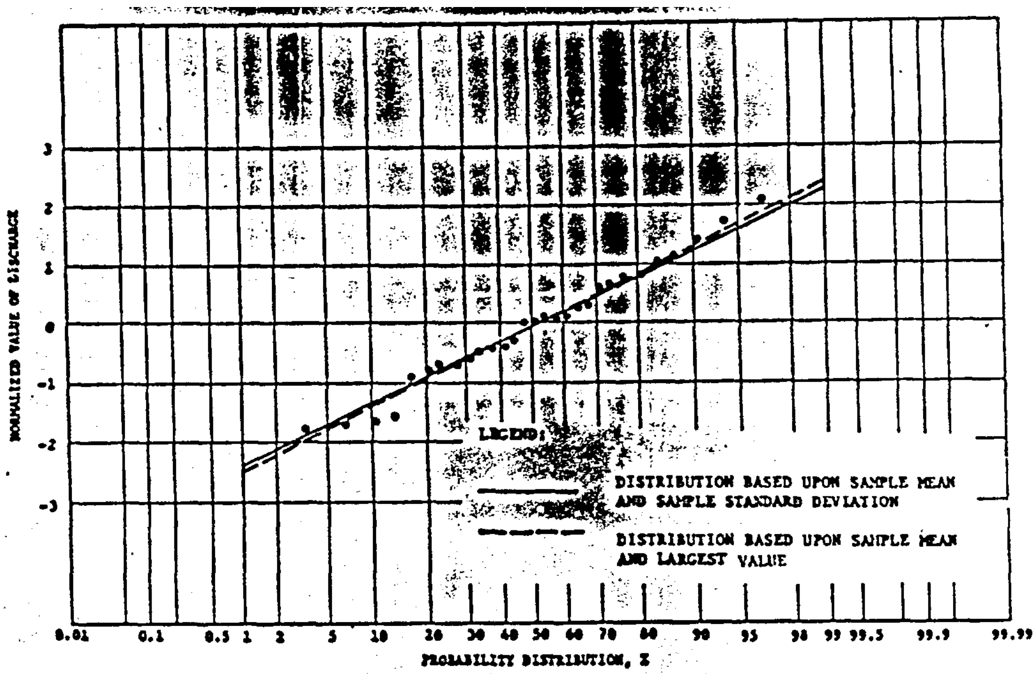

Figure 5.17 Daily samples of suspended solids loadings from a dry month (normal assumption).

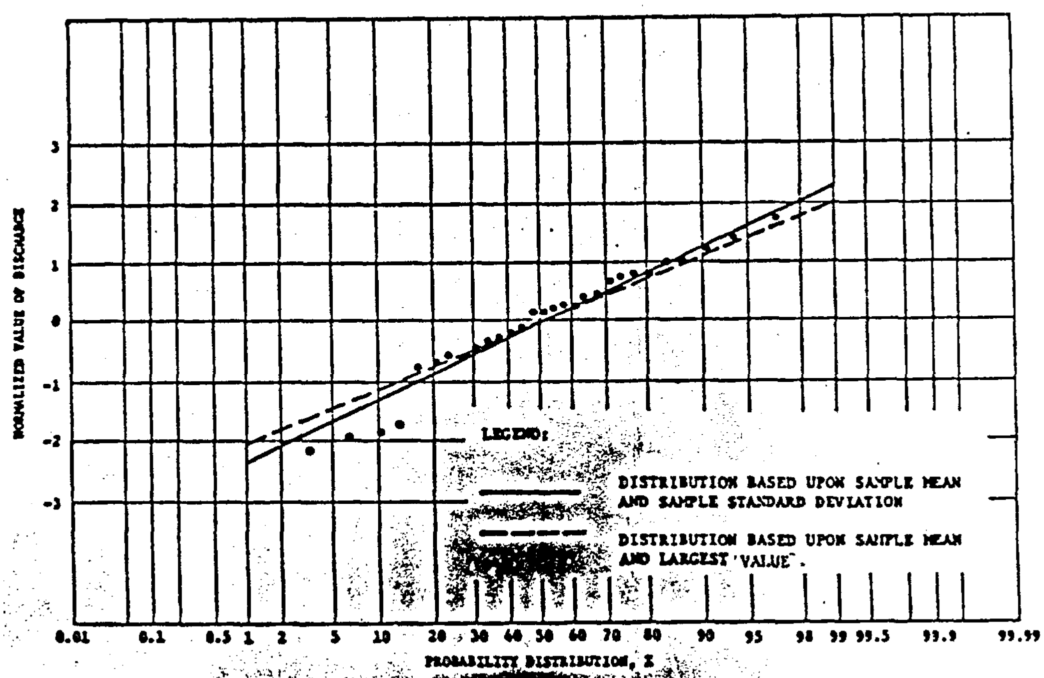

Figure 5.18 Daily samples of suspended solids loadings from a dry month (lognormal assumption).

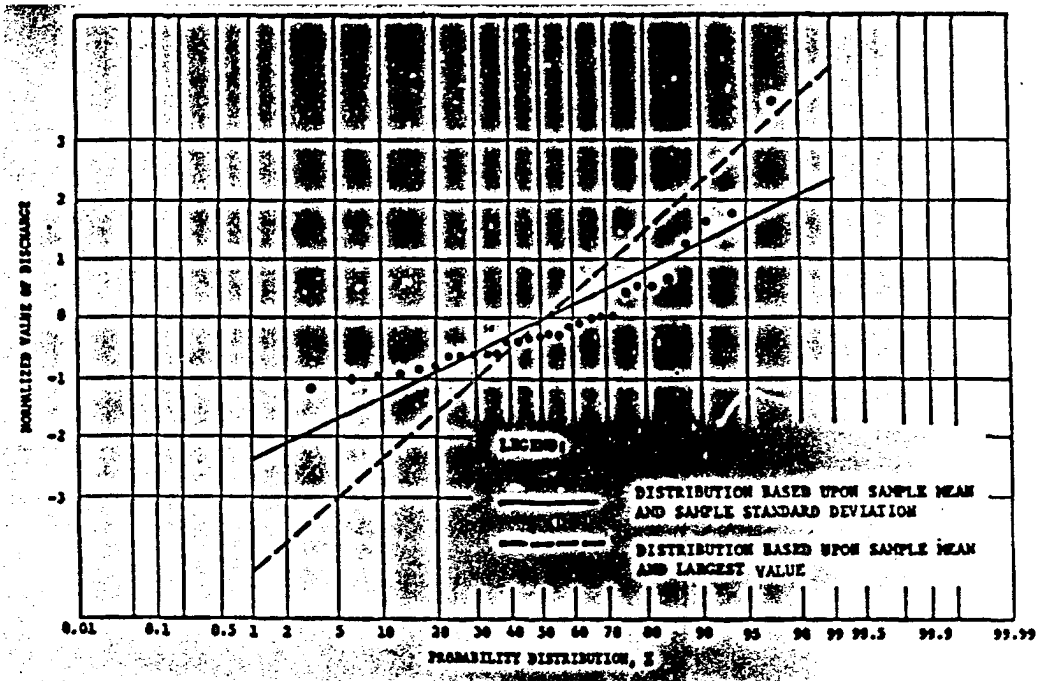

Figure 5.19 Daily samples of suspended solids loadings from a wet month (normal assumption).

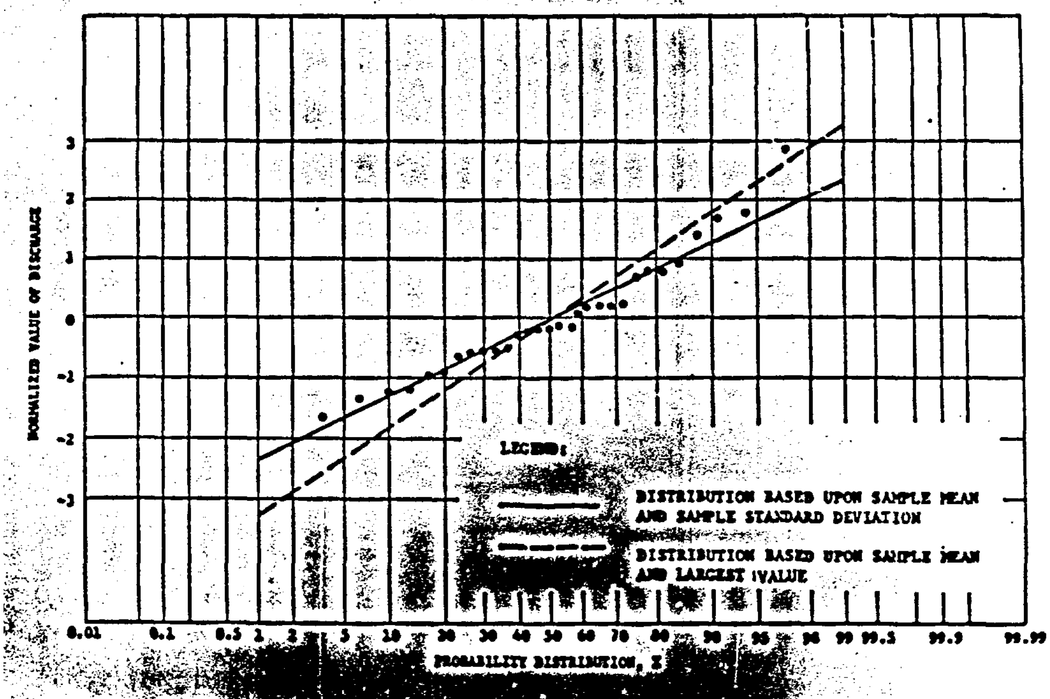

Figure 5.20 Daily samples of suspended solids loadings from a wet month (lognormal assumption).

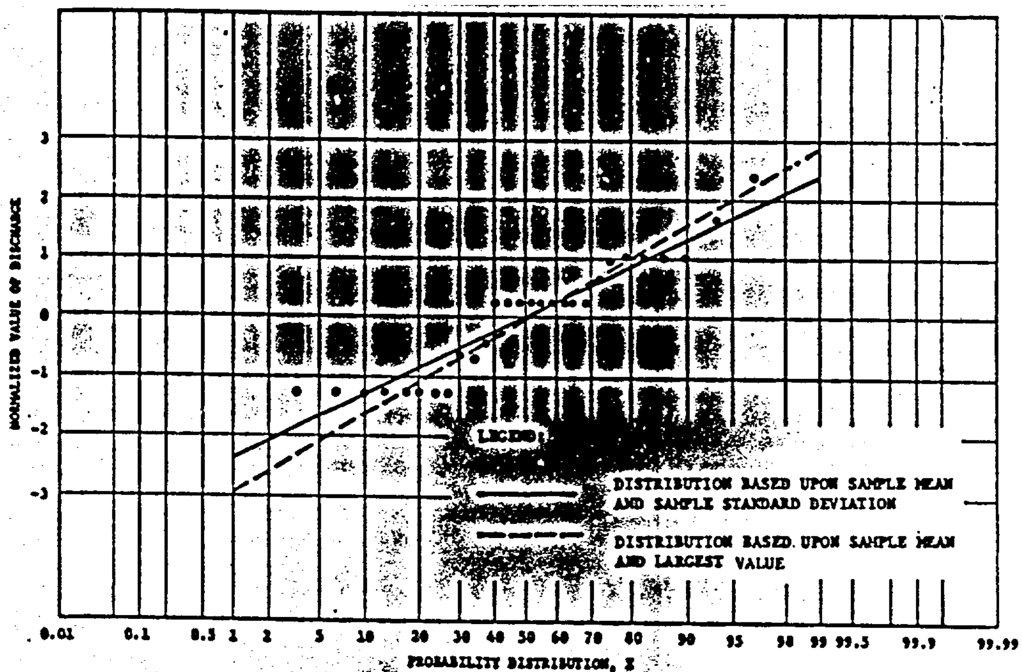

Figure 5.21 Daily samples of coliform loadings (lognormal assumption).

V.2 INITIAL STATISTICAL DESCRIPTION

The monitoring agency will have two types of data available from which it can initially determine the statistical characteristics of the effluent discharges:

- Self-monitoring data
- Compliance data

The self-monitoring reports will typically be sent to the appropriate regulatory agency on a quarterly basis. The reports will, at a minimum, contain the monthly maximum and monthly sample mean of the daily measurements (usually composite) of those constituents for which standards have been set. The report will also state the number of samples which were used to obtain the sample mean and maximum. Compliance data will also be available on the sources the monitoring agency has inspected as part of its compliance monitoring program.

When using the Resource Allocation Program for the first time, it is necessary to obtain an initial statistical description of all the effluent source constituents. This statistical description will be a function of self-monitoring data and compliance monitoring data gathered over many months. The procedure required to obtain the initial statistical description is shown in Figure 5.22. The various components of this procedure will now be discussed.

Aggregate Self-Monitoring Data

The procedure to obtain estimates of the mean and standard deviation from the sample mean and the maximum (given in Appendix A) requires that the number of measurements used to obtain the sample mean and the maximum be greater than three. If the number of measurements is three or less, the data over several months can be aggregated to obtain a

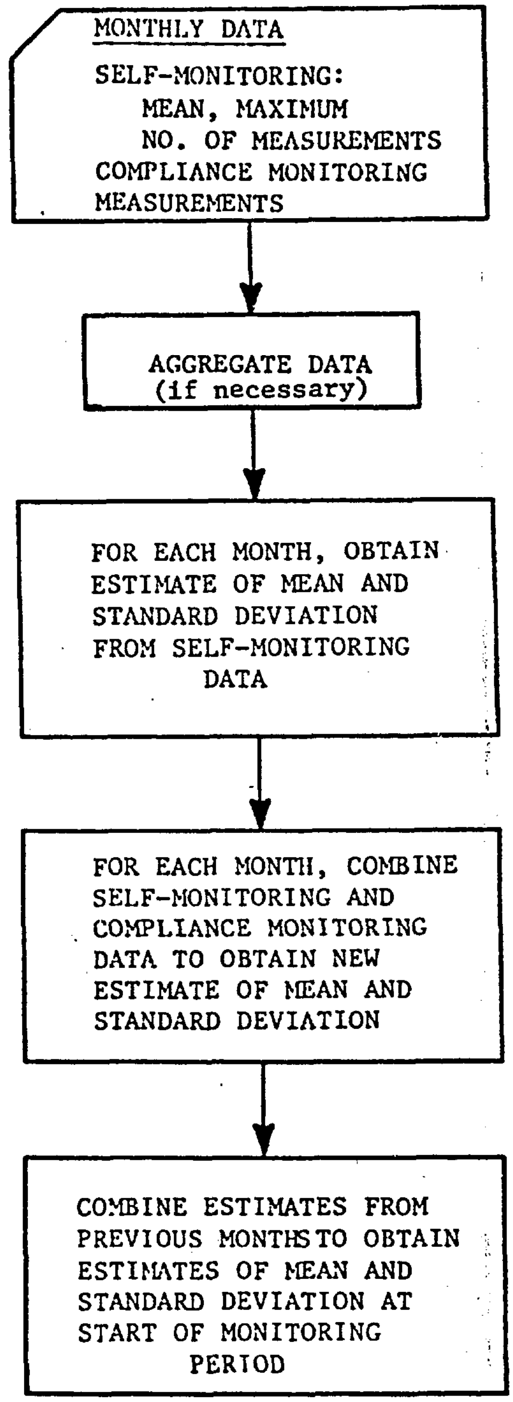

Figure 5.22 Initial statistical description procedure

sample mean and maximum based on more than three measurements. In this way the estimation procedures of Appendix B, which have been shown in Section V.1 to be applicable to describing the effluent statistics, can still be used. The aggregation procedure is straightforward. Let m_t, y_t and n_t, t = 1, 2,..., T, be respectively the sample mean, maximum and number of measurements in month t. Define the index sets $T_1, T_2, \ldots, T_s$ as follows: $T_1 = \{1, 2, \ldots, t_1\}$, $T_2 = \{t_1+1, \ldots, t_2\}, \ldots, T_s = \{t_{s-1}, \ldots, T\}$ so that

$$\hat{n}_i = \left[\sum_{t \varepsilon T_i} n_t\right] > 3$$

The data can therefore be treated as just coming from months $t_1, t_2, \ldots,$ T - these shall be called aggregated months. The means of the aggregated months are simply

$$\hat{m}_i = \frac{1}{\hat{n}_i} \sum_{t \varepsilon T_i} n_t m_t$$

and the maxima are

$$\hat{y}_i = \max_{t \varepsilon T_i} y_t$$

The number of measurements, n_i, in the aggregated months is greater than three and therefore the standard estimating procedures can be used to obtain estimates of the mean and maximum. Table 5.3 gives an example of the formation of the mean and maxima of the aggregated months.

Obtain Estimates of Mean and Standard Deviation From Monthly Self-Monitoring Data

The estimation procedures to obtain estimates of the mean and standard deviation for normal and lognormal processes are given in Appendix A, and their use was demonstrated in Section V.1.

Table 5.3. EXAMPLE OF AGGREGATION OF DATA

Original data				Aggregated data			
Month t	Number of measurements n_t	Sample mean m_t	Maximum y_t	Month i	Number of measurements $\hat{n}_i$	Sample mean $\hat{m}_i$	Max. $\hat{y}_i$
1	1	4	8				
2	2	5	7				
3	1	4	9	1	4	4.5	9
4	1	4	8				
5	1	4	7				
6	1	3	6				
7	2	4	8	2	5	3.8	8

Combine Self Monitoring and Compliance Monitoring Data

At this point in the procedure, estimates of the mean and standard deviation, based on self-monitoring data, are available for each month or aggregated month. These will be combined with the compliance monitoring data to btain new improved estimates. Since the monitoring agency will be collecting the compliance monitoring data, this data will be more reliable than the self-monitoring data. This should be taken into consideration in the method of combination.

The combination proceeds as follows: let $z_1, z_2, \ldots, z_c$ be c daily composite values obtained in the compliance monitoring program for a month. Let m and v be the estimated mean and variance for that month based on the self-monitoring data. Let n and v be the parameters which express the confidence in the mean and variance respectively. n and v are constants representing the equivalent number of measurements used to estimate m and v.* The values of n and v are set proportionally to the number of measurements, N, used to calculate the monthly mean and maximum, that is

$$n = h_n N \tag{5.1}$$

and

$$\nu = h_\nu (N-1) \tag{5.2}$$

where h_n and h_ν are design parameters.

---

* A discussion of these confidence parameters is given at the end of this section. They are also discussed in Appendix E. For further information see [7].

The compliance data and the monthly estimates are combined sequentially, using the updating formula described in Appendix E. First, the compliance data z_1, are combined with the self-monitoring estimates (m, n, v ν) using the update formula (E.3), yielding the posterior estimates (m_1, n_1, v_1, ν_1). The second compliance data z_2 are then combined with this estimate to yield a new estimate (m_2, n_2, v_2, ν_2). The process is repeated, until all the compliance data are used, to obtain a final monthly estimate. In order to give the compliance monitoring data more weight (since they will, in general, be more reliable) the values of ν and n used in (E.3a) and (E.3b) should be reduced by some constant, say γ; that is, ν and n should be replaced in the formula (E.3a) and (E.3c) by ν/γ and n/γ where $\gamma>1$ is a design constant.

As an example, consider tine case where the estimate of the mean, from self-monitoring data, is m = 100 and the estimate of the standard deviation is σ = 25. The confidence parameters are assumed to be n = 15 and ν = 10. Suppose compliance data for the month are also available with values z_1 = 115 and z_2 = 145. Let γ be equal 2. Using (E.3), z_1 can be combined with the estimates (m, n, v, ν) to yield (recall n' - 1 and ν' = 0)

$$m_1 = \frac{(n/\gamma)m + z_1}{(n/\gamma) + 1} = 101.8$$

$$n_1 = n + 1 = 16$$

$$v_1 = \frac{[(\nu/\gamma)v + (n/\gamma)m^2] + z_1^2 - ((n/\gamma) + 1)m_1^2}{(\nu/\gamma) + 1} = 543.7$$

$$\nu_1 = \nu + 1 = 11$$

The new estimate of the standard deviation is $\sigma_1 = \sqrt{v_1}$ = 23.3. The process is then repeated with (m_1, n_1, v_1, ν_1) replacing (m, n, v, ν) and z_2 replacing z_1 to yield

$$m_2 = 106.6$$

$$n_2 = 17$$

$$v_2 = 715.27$$

$$\nu_2 = 12$$

The new estimate of the standard deviation is $\sigma_2 = 26.7$. Figure 5.23 shows how the assumed density function would change for this example.

Combine Estimates from Several Months

The final step in obtaining an initial statistical description is to combine the estimates from several months to obtain an estimate of the mean and standard deviation at the start of the monitoring, period. The estimates are combined by sequentially using the Bayesian update formula given in Appendix E. If the mean m_t and the variance v_t, along with the confidence parameters n_t and ν_t, are available for months t = 1, 2,..., T, the final estimates would be obtained by first combining (m_1, n_1, v_1, ν_1) and (m_2, n_2, v_2, ν_2) using (E.3) yielding $(m_2', n_2', v_2', \nu_2')$. Then $(m_2', n_2', v_2', \nu_2')$ would be combined with (m_3, n_3, v_3, ν_3) to yield $(m_3', n_3', v_3', \nu_3')$. This process would be repeated until the estimate $(m_T', n_T', v_T', \nu_3')$ is obtained, which is the estimate to use in the priority setting procedure.

Confidence Parameters

In order to use the Bayesian update formula, it is necessary to specify the confidence parameters n and ν. These parameters describe one's confidence in the estimates of the mean and standard deviation. For the case when the statistics of the process are normal or lognormal and stationary, and the estimates used are the sample mean and sample

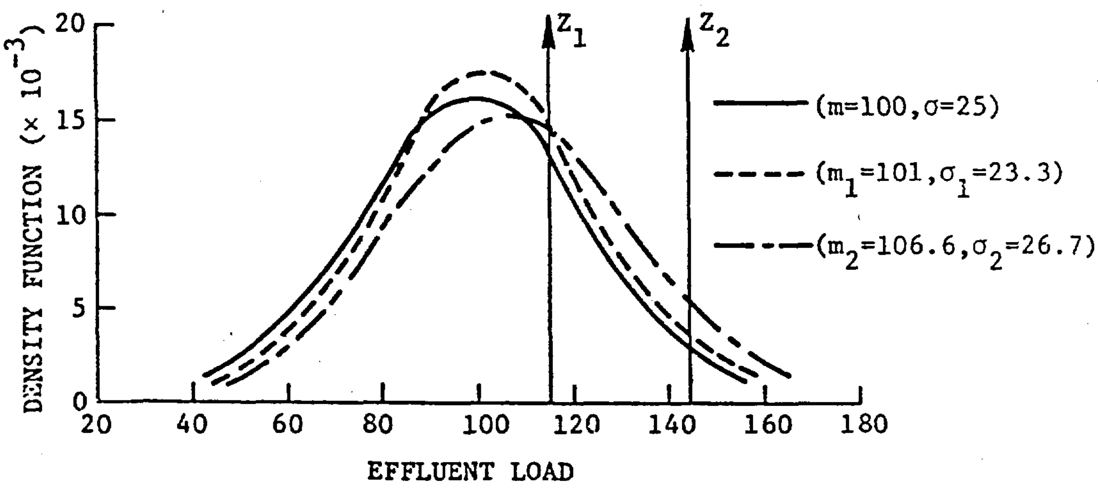

Figure 5.23 Example of inclusion of compliance monitoring information

standard deviation of N data points, n would be set equal to N and ν equal to N-1. In the present case, the statistics are not exactly normal or lognormal, the process is not, in general, stationary, and the estimate of the standard deviation is not the sample standard deviation. For these reasons the specification of n and ν must be based on the following subjective factors:

(1) In order to take trends into account and to discount past information, the value of n and ν in the updating formula must not be allowed to get too large. This can be accomplished by requiring $n \leq k_n n'$ and $\nu \leq k_\nu \nu'$ in (E.3) where k_n and k_ν are given constants. Therefore, if the update formula results in $n > k_n n'$ or $\nu > k_\nu \nu'$ then set $n = k_n n'$ and $\nu = k_\nu \nu'$.

(2) For the normal case, the estimate of the mean is the sample mean and so a reasonable value for h_n in (5.1) is 1 for this case. The estimate of the mean for the lognormal case should. also be very efficient, and so again a value of $h_n = 1$ is suggested.

(3) The efficiency of the estimates of the standard deviation obtained from the sample mean and maximum is unknown. They should, however, be on the same order as the estimates of the standard deviation that can be obtained from the range (the range is the difference between the largest and smallest values from a sample). It is shown in Appendix A that the relating efficiency of this estimate varied from 1.0 when there were two samples to 0.49 when there were 50 samples (see Table A.3.3). It is suggested that h_ν be set equal to the value of relative efficiency indicated in Table A-3.3.

V.3 UPDATE OF STATISTICS

In the previous section, a procedure was given to obtain the statistical characteristics of the effluent sources at the commencement of the use of the Resource Allocation Program. The Resource Allocation Program will be used on a periodic basis to obtain the sampling frequencies for each following monitoring period. At the same time the monitoring agency will continue to receive self-monitoring and compliance data. The purpose of this section is to describe how this data should be used to obtain an updated statistical description.

The update procedure is identical to the procedure described in Section V.2, with the small exception that the old statistical characterization is used as a starting point in the procedure. To be precise, the statistical update procedure follows the Initial Statistical Description procedure (see Figure 5.22) in that first the new monthly data are aggregated, if necessary, to obtain sample sizes greater than 3; estimates of the mean and standard deviation based on the self-monitoring data are then obtained. The Bayesian update formulas (Appendix E) are then used to combine the compliance monitoring data and the monthly statistics based on self-monitoring. At this point the original statistical description of the effluent and the new monthly statistical description based on the new data are available. These are combined sequentially, starting with the original statistics, using the Bayesian update formula, thereby obtaining an updated statistical description.

SECTION VI

"COST" OF UNDETECTED VIOLATIONS

The purpose of compliance monitoring is to ascertain whether pollutant loads in permitted discharges are in compliance with the limits specified in the permits. In determining how often to sample a particular effluent source in a monitoring period, several factors should be taken into account, including

- How often a violation is expected
- The expected magnitude of the violation
- The toxicity of the pollutants
- The assimilative capacity of the receiving waters at the discharge point.

A performance index called the "cost" of undetected violations, which depends on these factors, is derived in this section. The decision variable is the number of times each source is to be monitored in a monitoring period (i.e. the sampling frequencies). The "cost" is defined as the expected value of the damage caused by the pollutants of sources not found in violation of their standards. "Costs" are only associated with undetected violations, because if a source is monitored and found in violation of a standard, then the monitoring agency has done its job and no "costs" should therefore be associated with that visit.

The performance index depends on (i) the statistical descriptions of the pollutant loadings, (ii) the damage functions, (iii) the relationship between the pollutant loading and the concentration of the corresponding water quality indicator in the stream, and (iv) the effluent standards. The "costs" discussed here are environmental costs and not monetary costs. The value of the performance index will not correspond to a dollar amount. This is the reason that the word "cost" is being set off in quotation marks.

The "cost" of undetected violations for a given source can be written as the product of two terms. The first term is the expected damage caused by the pollutants of the source. This damage is defined as the environmental damage to the receiving waters caused by the effluent source's constituents. Since the environmental damage due to a specific concentration of pollutant in the stream varies greatly with the natures of the pollutant, it is necessary to define a damage function. This damage function assigns a value to a given concentration of pollutant in the receiving waters. In this way, for example, a small concentration of mercury and a relatively large concentration of suspended solids can give the same value of damage. The second term in the "cost" of undetected violations is the probability that no violation is detected at the source. This term reflects the fact that as a source is sampled with increasing frequency, the probability that a violation will go undetected will decrease. To recapitulate, the "cost" of undetected violations from a source is the product of two terms:

- The expected damage from the source
- The probability that the source will not be in violation

The remainder of this section will (i) investigate the effect on the receiving waters of the effluent load, (ii) define damage functions for various pollutants, and (iii) derive in detail the "cost" of undetected violations.

VI.1 EFFECT ON AMBIENT QUALITY DUE TO EFFLUENT LOADS

Receiving water damages are assumed to be a direct function of the constituent concentrations. The method of estimating receiving water concentrations resulting from various types of effluent discharges is described below.

In the computation of receiving water concentrations, "far-field" spatial and temporal scales are used [8]. In practice, the far-field concept restricts the spatial scales of interest. Streams and vertically well mixed estuaries and reservoirs can be treated as one dimensional flows with only longitudinal variations in concentration. Effluent discharges located in very close proximity may be "clustered" and treated as discharges entering a single point.

The far-field concept also permits the use of net flows and velocities in estuaries. In the short term, estuarine flows primarily fluctuate in a cyclic manner related to tidal heights, but the long term trend is for the estuarine waters to flow toward the sea at a magnitude approximately equal to the river flow into the estuary. Using this concept, the advective nature of estuaries is related only to the net seaward flow, which can be estimated using the sum of incoming river flows.

The far-field approach enables usage of simple water quality modeling techniques presented in [9]. Models which describe the three dimensional aspects of mixing in the near field with temporal variations are not needed. Since Water Quality Standards are given for areas outside of some mixing zone, the use of the far-field concept fits well with the law, permits the development of tractible procedures for deriving concentration, and enables subsequent damage function predictions.

Constituent Selection

Table 6.1 lists the water constituents which have been considered in this study. The different types of constituent behavior are discussed in the following subsection. These constituents were selected on the basis of their presence in the existing Federal Effluent Guidelines [10-26], and their probable presence in various industrial and domestic effluent discharges. Except for dissolved oxygen, receiving water concentrations of each of the listed constituents are directly proportional to the magnitudes of their respective effluent loadings. Adverse effects of effluents upon dissolved oxygen are indirectly caused by loadings of biochemical oxygen demand (BOD) and chemical oxygen demand (COD). The impact upon dissolved oxygen due to a BOD or COD load can be expressed in terms of a simple transfer coefficient multiplied by the receiving water concentration of BOD or COD caused by the load. Therefore, the damages due to loadings of BOD and COD, as well as all the other pertinent constituents, can be found directly through their predicted concentrations along the stream.

Stream Impact Characterization

For purposes of this study, rivers, estuaries and reservoirs are treated as one-dimensional systems with only net downstream velocities. In this context, all of these receiving waters are treated as streams. The mathematical models used to describe the impact of the waste constituents in streams are classified as either conservative, or non-conservative non-coupled. The analysis of the coupled constituent, dissolved oxygen, is performed through modeling of the non-conservative, non-coupled constituents, BOD and COD.

Conservative constituents are those which do not decay in the stream with time. The constituent concentration is reduced only by dilution. Figure 6.1 illustrates the spatial characteristics of a conservative constituent with a single waste source entering the stream. The only factors affecting the stream concentration of the j^{th} conservative

Table 6.1. BEHAVIOR OF WATER CONSTITUENTS

Constituent Name	Behavior *	Constituent Name	Behavior
Aluminum (total)	C	Lead (total)	NN
Ammonia	NN	Manganese (total)	NN
Dissolved Oxygen	NC	Mercury	NN
Total Inorganic Carbon	C	Nickel (total)	NN
Chloride	C	Nitrogen	NN
Chloroform Extract (measure of taste & odor potential)	NN	Oil-Grease	NN
Chromium (total)	NN	pH-MIN	NN
Coliforms-Total	NN	pH-MAX	NN
Coliforms-Fecal	NN	Phenol	NN
Copper (total)	NN	Phosphorus	NN
Cyanide	NN	Solids-Dissolved	C
Fluoride (total)	C	Solids-Suspended	NN
Iron (total)	NN	Temp. Diff.	NN
		Tin (total)	NN
		Zinc (total)	NN

*C - conservative

NN - non-conservative, non-coupled

NC - non-conservative coupled

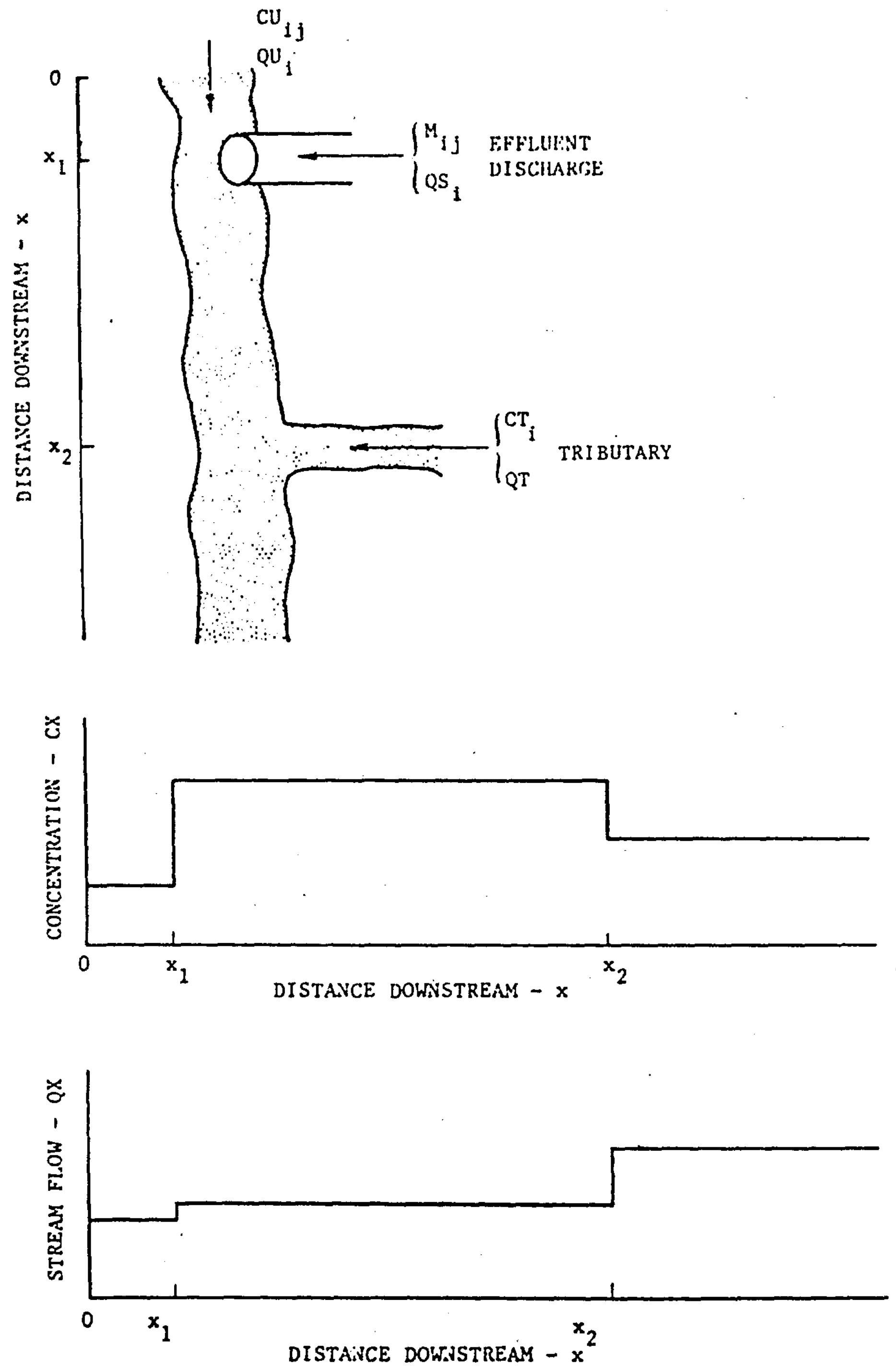

Figure 6.1 Stream characterization of conservative constituents [B].

constituent due to the i^{th} effluent source are the upstream flow in the stream QU_i, the net* effluent mass load M_{ij}, mean effluent flow rate QS_i, and the upstream concentration CU_{ij}. The flow in the stream below discharge i may be written as

$$QX_i = QU_i + QS_i \tag{6.1}$$

The concentration in the stream immediately downstream from the i^{th} source is†

$$CO_{ij} = \frac{M_{ij} + CU_{ij}\ QU_i}{QX_i} \tag{6.2}$$

For conservative constituents this stream concentration persists downstream until new effluent or water sources either dilute or add to it.

Non-conservative, non-coupled mathematical models are used to characterize water quality constituents whose concentrations vary with both time and dilution. For these constituents first-order kinetics are assumed and a decay rate coefficient assigned for each parameter. Figure 6.2 illustrates the case of a non-conservative, non-coupled constituent. It assumes that the physical characteristics of the stream are uniform over the distance shown so that the decay coefficient (k) and the stream velocity (v) are constant. The equation describing the steady-state spatial characteristics of a non-conservative, non-coupled constituent below a single source (downstream of x_1 in Figure 6.1) is

$$CX_{ij} = \left(\frac{M_{ij} + CU_{ij}\ QU_{ij}}{QX_i}\right) e^{-K(x-x_1)/v}$$

* The word "net" is used to account for industries that withdraw polluted water from a stream and then discharge it in somewhat changed form. Those industries should not be penalized for their polluted intake water.

† Care must be taken in maintaining proper units in this equation. In this regard the following suggestions are made. For temperature the constitutent mass (M_{ij}) should be expressed in terms of heat (temp x flow), for pH the mass term should be expressed as the net effluent ion concentration multiplied by its flow (see Appendix C for more details on pH), and for coliforms the net effluent coliform concentration (MPN/100ml) should be multiplied by its flow.

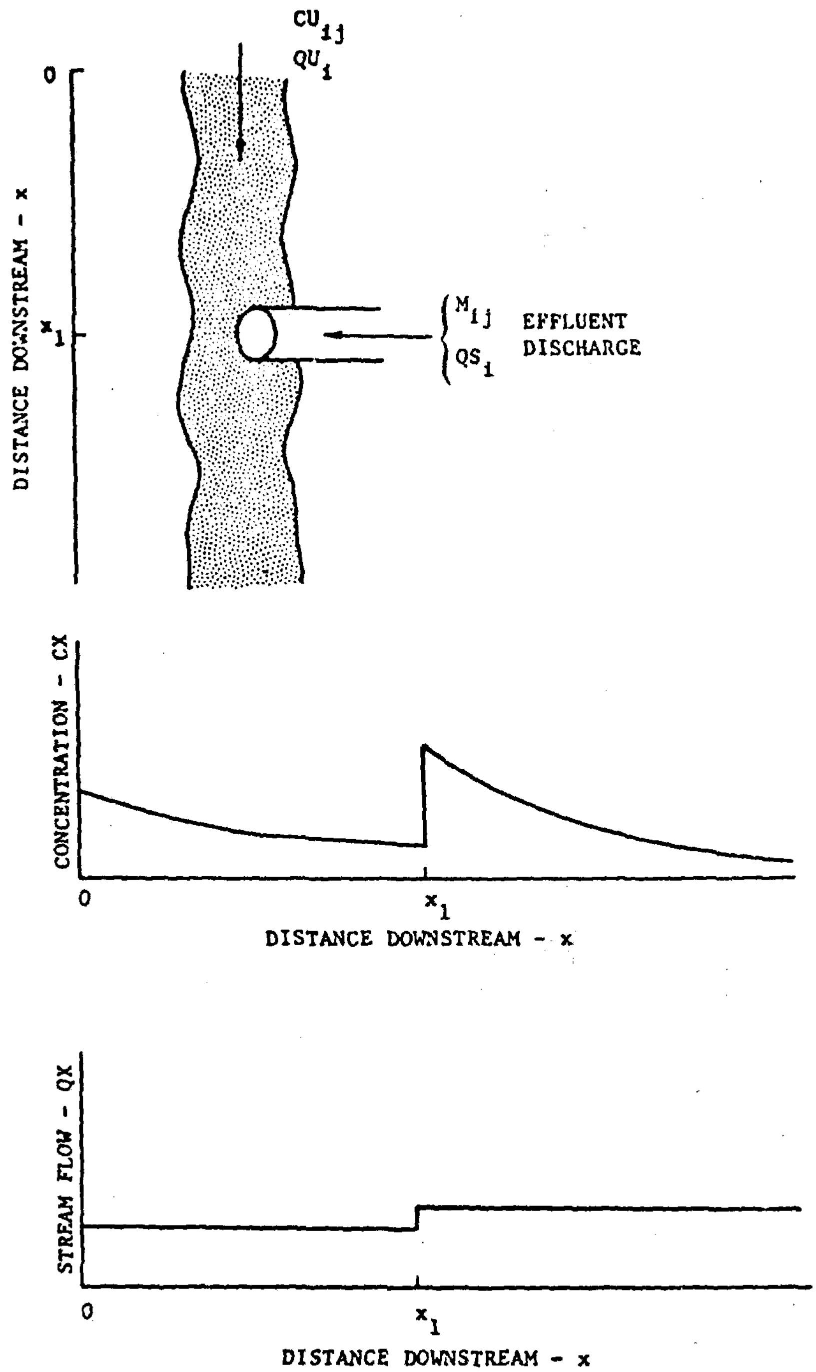

Figure 6.2 Stream characterization of non-conservative, non-coupled constituents [B].

An effluent damage is considered to be a function of its maximum impact at any point of the stream. From Figures 6.1 and 6.2 it can be seen that the maximum concentration impact due to discharge of a non-coupled constituent occurs at the discharge point. Therefore, the damage functions can be related to the initial diluted stream concentration of constituents:

$$\text{Damage} \propto CO_{ij} = \frac{M_{ij} + CU_{ij}\ QU_{ij}}{QU_i + QS_i} \qquad (6.4)$$

The input mean stream flows and discharge flows are usually available from historical data. The varying mass loads are input in statistical form as shown in Section V. A discussion concerning the value of upstream concentration to use in (6.4) is given in Section VI.2

Dissolved Oxygen Damages

The presence of BOD or COD in receiving waters induces a two step reaction in which BOD (or COD) decays, in the process depleting the available dissolved oxygen, and the oxygen replenishes itself through natural air-water interaction. The difference between the saturated level of dissolved oxygen (DOSAT) and the actual level is called the dissolved oxygen deficit (D). The maximum dissolved oxygen deficit due to BOD load from effluent i ($D_{i,BOD}$) can be approximated in terms of a transfer coefficient (K_{BOD-DO}) multiplied by the initial stream BOD concentration [9], i.e.,

$$D_{i,BOD} = (K_{BOD-DO})(CO_{i,BOD}) = K_{BOD-DO}\left[\frac{M_{i,BOD} + CU_{i,BOD}QU_i}{QX_i}\right] \qquad (6.5)$$

Similarly for COD

$$D_{i,COD} = (K_{COD-DO})(CO_{i,COD}) = K_{COD-DO}\left[\frac{M_{i,COD} + CU_{i,COD}QU_i}{QX_i}\right] \qquad (6.6)$$

A simple method for obtaining the transfer coefficients, K_{BOD-DO} and K_{COD-DO}, is presented in Appendix F.

The damage due to a BOD or COD load is related to the minimum expected level of dissolved oxygen due to the load. This minimum DO level is computed as

$$DOMIN_{i,BOD} = \begin{cases} CO_{i,DO}-D_{i,BOD}, & \text{if } CO_{i,DO} \geq D_{i,BOD} \\ 0 & \text{, otherwise} \end{cases} \tag{6.7}$$

for BOD and

$$DOMIN_{i,COD} = \begin{cases} CO_{i,DO}-D_{i,COD}, & \text{if } CO_{i,DO} > D_{i,COD} \\ 0 & \text{, otherwise} \end{cases} \tag{6.8}$$

for COD. $CO_{i\ DO}$, the dissolved oxygen concentration at the point of discharge, is

$$CO_{i,DO} = \frac{CS_{i,DO}\ QS_i + CU_{i,DO} \cdot QU_i}{QX_i} \tag{6.9}$$

where $CS_{i\ DO}$ and $CU_{i,DO}$ are respectively, the concentration of DO in the source effluent and in the receiving waters upstream from the source. (6.7) and (6.8) are conservative (i.e. low) estimates of DOMIN. The transfer coefficient, K_{BOD} DO in (6.5) is derived assuming the DO is at saturation at the point of BOD discharge. If DO is not in saturation, then the decrease in DO will be somewhat less then the value given in (6.5)-(6.6).

VI.2 DAMAGE FUNCTIONS

The damage function relates environmental damage to a given concentration of various pollutants in a stream. There have been two basic approaches to characterizing damage functions: (1) a subjective definition [27], [28], [29] where the shape of damage function curve was related to, for example, the effect on fish, fitness to drink, fitness for recreation, etc.; or (2) an economic definition [30], [31] where the damage is related, for example, to the cost of returning the water to a point where pollutant levels are below some standard. Both of these types of damage functions have drawbacks. The "subjective" damage function is hard to quantify into a single function. Most bodies of water have varied uses and a particular pollutant will affect the various uses to different degrees. Even if only a single water use is affected, there is disagreement for most pollutants as to what level of pollutant causes the water to be of acceptable quality or to be polluted. The "economic" damage function, on the other hand, can yield costs which are related to attributes other than environmental damage. If, for example, the damage is related to the cost of restoring the quality of the stream then a pollutant which is more difficult to remove or dilute but does little environmental harm will cause more "damage" than one which is easier to remove but causes greater environmental damage. The economic approach also has the problem that it may be difficult to obtain the data needed to define the damage function.

The "subjective" damage function has been chosen for this study. It has the advantage of reflecting environmental damage without bringing into consideration unimportant factors such as cost of water for dilution. Also, for the purposes of the priority procedure, the damage functions are only used so that concentrations of various pollutants can be compared with respect to environmental damage. The actual values given to the damage functions and the decision as to when a concentration of a pollutant causes the waters to be "polluted" are not that important as long as the rules for defining the damage functions are consistent.

The damage function is defined as a piecewise linear function where a numerical value is given to each "Level of Damage" - the values 0, 2, 4, 6, 8 and 10 correspond to "none“, "excellent", "acceptable", "slightly polluted", "polluted", and "heavily polluted", respectively. This type of damage function closely follows the approaches used by Prati [27], Horten [28], and McClelland [29]. Using [28] - [29] and [32] - [34], damage functions were defined for 26 water quality indicators. These damage functions are given in Table 6.2. Figure 6.3 gives an example, in graphical form, of a damage function; the indicator considered is suspended solids.