Title: Statistical Basis of Standards

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Objectives:

Research has shown that use of the 7-day 10-year low flow as a critical streamflow may be an overly conservative basis for setting standards. The objective of the proposed research is to study the effect of different critical low flows on water quality parameters.

Procedure:

The first part of the research will be to search the literature to determine what research has been done in the area. In addition, any states using a low-flow standard other than the 7-day 10-year low flow will be canvassed to determine the rationale and to assess the impact of its use.

The second phase of the study will be to perform a number of analyses on streamflow data. The analyses will be aimed at comparing the 7-day 10-year low flow with other possible measures, for example, a certain flowrate per sqaure mile of drainage area. A third phase will use the results of the second part of the study to assess the effect that the use of different critical low flows may have on the concentrations of key water quality parameters.

Expected Results:

A technical report will detail all findings of the research including a literature review, procedures and results of statistical analyses, and pertinent conclusions and recommendations.

Duration: Two years

Cost: $29,000

Name of Project: Statistical Basis of Standards

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Progress Report: The project started in January of 1987, and since that time two tasks have been addressed: (1) further definition of the goals of the project and (2) initiation of a thorough literature review.

The scope of the project has been more thoroughly defined to include an analysis of water quality excursions under the existing standard for municipal wastewater dischargers and to "translate" this probability of excursion to non-point source dischargers. The intent of this exercise is to allow creation of discharge permits for non-point source dischargers which are compatible with existing regulations.

The research will be divided into three phases, with possible addition of a fourth.

1. Assess the statistical nature of excursions resulting from wastewater discharges, based on the distributions of the four controlling parameters, upstream flow, discharge flow, upstream concentration, and discharge concentration.

2. Analyze the nature of non-point source discharges to determine statistical distributions of the four controlling parameters mentioned above.

3. Determine the statistical nature of excursions for non-point source discharges, and compare the excursions for non-point source discharges to those for point source.

4. If time permits, extend the analysis for non-point source discharges to lakes and oceans.

A literature review has been conducted on the statistical nature of standards for traditional wastewater dischargers. This review utilized the computerized file, Water Resources Abstracts, maintained by USGS. In addition, traditional approaches, including scanning of recent pertinent literature and relevant list of references, were used. The search will be expanded to include any research that has been conducted specifically on non-point discharges.

More detail on the specific goals of the project and the results of the literature review can be found in a separate writeup.

<u>Research Timetable</u>: A rough research timetable is shown below:

Summer 1987
- Complete literature review.
- Compile data necessary for statistical analysis of point source dischargers.
- Start to conduct statistical analysis.

Fall 1987
- Complete statistical analysis of point source discharges.
- Search for relevant data on non-point source discharges.

Spring 1988
- Compile data on non-point source discharges.
- Investigate distributions applicable to non-point source discharges.

Summer 1988
- Perform statistical analysis on non-point source discharges.
- Investigate management schemes to assure compliance.
- Investigate non-point source discharges to lakes and oceans (if time).

Fall 1988
- Compilation of results.
- Draft of report.
- Application to lakes and oceans (if time).

Spring 1989
- Preparation of final report.

Progress Report

Statistical Basis of Standards

Submitted to

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Water Pollution Control

by

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Overview

The overall goal of the project is to study the statistical nature of existing water quality standards, and to apply the findings to the development of standards for non-point source pollution control. Water quality standards are typically based on the 7Q10 low flow. Since the 7Q10 flow is exceeded on the order of 99% of the time (Male and Ogawa 1982, Ray and Walker 1968), it was thought that the water quality standards would be violated 1% of the time. However, during previous work (fall 87), a statistical analysis of a point source discharge which considered variations in all the variables in the mass balance equation showed that the excursion frequency was 2-3 times higher than that which would have been predicted based on the 7Q10 flow alone. Because of its importance in developing uniform standards for point and nonpoint sources of pollution, the reason for the higher excursion frequency was investigated further.

Also during previous work, a Monte Carlo simulation program for combined sewer overflows was written in which the time between storms was modeled using the exponential distribution (EPA, 1979A), the duration of the storms were set at one day, and all correlations were assumed to be zero. A major concern at the time was whether the zero correlation assumption was valid. To verify this assumption, correlations between flow and concentrations were determined, and compared with results reported in the literature.

This report discusses this work and also compares the results of Monte Carlo simulations with a moment approximation method (DiToro, 1984). The moment approximation method assumes all distributions are lognormal and can only account for correlations between stream flow and effluent flow. The moment approximation method has been programmed on the Lotus 123 spreadsheet for ease of use.

Excursions Due to Point Source Discharges

Flow and NH3 concentration data from a point source discharge and an upstream water quality monitoring station were fit to several distributions, with the best fitting distribution, values of the parameters, mean, and variance listed in table 1. In another analysis, the 7Q10 was found to be 32 cfs, and that it was exceeded 99% of the time. Using average values for upsteam NH3 concentration, effluent NH3 concentration, and effluent flow, the downstream NH3 concentration (D) at 7Q10 conditions was calculated as follows:

$$D = \frac{(32cfs)(.483\ mg/l) + (6.8cfs)(18.4\ mg/l)}{32cfs + 6.8cfs} = 3.63\ mg/l$$

For the purpose of this analysis, downstream concentrations of NH3 greater that 3.63 mg/l will be considered an excursion. Using Monte Carlo simulation with the distributions and parameters listed in table 1, the excursion frequency was found to be 2.7%. This is almost 3 times higher than that which would have been predicted based on the river flow alone. To see what effect probability distributions for upstream concentration, effluent concentration and effluent flow would have on the excursion frequency, the Monte Carlo simulations were repeated for the following cases:

1) Lognormal distribution for river flow, and average values for effluent flow, effluent concentration, and upstream concentration;
2) Lognormal distributions for upstream flow and upstream concentration, and average values for effluent flow and effluent concentration;
3) Lognormal distributions for upstream flow, and upstream concentration, Uniform distribution for effluent concentration, and an average value for effluent flow.

The results of these simulations are plotted in figure 1, where F-LN = river flow-lognormal, C-LN = river concentration-lognormal, e-Unif = effluent concentration-uniform, and q-nonpara = effluent flow-nonparametric. For clarity, only the highest 10% are shown.

Figure 1 shows that if the downstream concentration of NH_3 depended only on river flow, the excursion frequency would be 1.1 %, which is very close to what would have been predicted based on the 7Q10 flow. However, as probability distributions for the other variables in the mass balance equation are considered, the excursion increases to nearly 3%.

To see what effect adding correlations would have on the excursion frequency, the simulations were repeated with the correlations between river flow and river concentration equal to .5 and -.5. These results are plotted on figure 2, where the correlations between river flow and river concentration are shown as rFC. It was not possible to consider correlations between the other variables because the distributions are not the same.

Figure 2 shows that, as expected, a positive correlation between river flow and river concentration reduces the excursion frequency. A positive correlation might occur if storm were to increase both the river flow and concentration due to runoff. Interestingly, a negative correlation seemed to have little effect on the excursion frequency. In a similar analysis, Warn and Brew (1980) observed that a correlation of -.8 had little effect on the 5% exceedence concentration. Warn and Brew suggested that the reason for this is that, although the downstream concentration will be higher at low flow conditions with a negative correlation, under high flow conditions the situation is improved. Therefore the two effects tend to compensate.

Because of the importance of the excursion frequency in relating point source water quality standards to non-point sources, the mathematical basis for the above results will be discussed in more detail.

Mathematical Basis of Excursion Frequency

The following discussion is based on analytical procedures developed by Warn and Brew (1980) and DiToro (1984), in which all variables in the mass balance equation are assumed to be log-normally distributed.

1) $$T = \frac{FC + qe}{F + q}$$

where

F = upstream flow
C = upstream concentration
q = effluent flow
e = effluent concentration
T = downstream concentration

Warn and Brew (1980) show that T is approximately lognormal and therefore the percentiles of T are given as:

2) $$T_{\alpha} = \exp(\mu_{1T} + z_{\alpha}\sigma_{1T})$$

where

T_{α} = percentile of the downstream concentration

μ_{1T} = the mean of logged downstream concentration

σ_{1T} = the standard deviation of logged downstream concention

z_{α} = α percentile of a standard normal random variable

For example, the downstream concentration which has an excursion frequency of 1% would be the 99th percentile (α = .99). From standard normal probability tables, $z_{.99}$ = 2.327. Equation 2 can be rewritten as:

$$3) \qquad T_{.99} = \exp(\mu_{1T} + 2.327(\sigma_{1T}))$$

Equation 3 shows that an increase in the variance of T $\left(\sigma^2_{1T}\right)$, would cause an increase in the 99th percentile of T. DiToro (1984) shows that the variance of F, C, e, and q are all proportional to the variance of T. Current wasteload allocation procedures do not account for the variance of C, q, and e. By including the variablilty of C, q, and e in the mass balance equation, such as through the use of Monte Carlo simulation, the variance of T will increase, which in turn causes an increase in the excursion frequency.

Another way of including the variability of F, C, q and e in the mass balance equation is to use the moment approximation technique (DiToro, 1984), which has been programmed on the Lotus 123 spreadsheet. Using the arithmetic averages and variances listed in table 1, the percentile of the downstream concentration less than 3.63 was found to be 97.1%, which gives an excursion frequency of 2.9%. Table 2 summarizes the results of the moment approximation calculations. The excursion frequency calculated by the moment approximation is very close to the 2.7% calculated by the Monte Carlo method. If the variances of C, q, and e are set to zero, then the excursion frequency becomes 1.1%, which is the same value calculated by the Monte Carlo method, and which is very close to the 7Q10 excursion frequency.

The moment approximation method is only an approximation. DiToro (1984) notes that since the problem is symmetric, an internal check of the accuracy can be made by interchanging F and C with e and q. If this is done, the excursion frequency becomes 4%, and the downstream concentration at the 97.1 percentile is 4.04. Based on comparisons with symmetical inversions performed by DiToro for several test cases, this is thought to be an acceptable deviation.

An exact quadrature method has also been developed by DiToro (1984), but conceptually it is harder to understand. The quadrature method is currently being studied to determine its applicability to the research project.

Correlations

In developing the CSO Monte Carlo simulation program (fall, 87), all correlations were assumed to be zero. They were set to zero partly because the computational simplification allows other distributions besides normal and lognormal to be used. They were also set to zero because of the difficulty in calculating the cross correlations. In order to calculate the cross correlation between two random variables, it is necessary to have values from both distributions averaged for the same duration at the same time. Therefore, it may not be possible to calculate cross correlations between all of the variables because of differences in averaging or sampling times. However, DiToro (1984) was able to calculate the cross correlations between all variables in the mass balance equation for a data set from South Dakota which included 15-20 runoff events. DiToro found that the correlations were insignicant and did not effect the calculations.

There have been studies which have evaluated the cross correlations between these variables using Monte Carlo simulation. Crabtree, Cluckie, and Forster (1986) varied the cross correlation between river flow and effluent flow from .35 to .85 for BOD and NH3 data sets, and found no significant effect on the 95 percentile of the downstream concentration.

Warn and Brew (1980) evaluted the cross correlations between all variables in the mass balance equation and found that only high correlations between upstream flow and effluent concentration had a significant effect on the mean of the downstream concentration. However, Warn and Brew concluded that these correlations are unlikely to be present in real problems.

Although it is difficult to obtain correlations between a discharge and a river, correlations between river flow and concentration and between effluent flow and concentration can be calculated quite easily. For the Quinnipiac river data set, flows and the corresponding concentration were tabulated and the correlation calculated using standard statistical methods. A similiar procedure was followed using the Wallingford wastewater treatment plant data set. The cross correlations between flow and concentration for the Quinnipiac river and Wallingford wastewater treatment plant are shown in tables 3 and 4, respectively. As can be seen from table 3, there are significant correlations between flow, total solids, and dissolved solids. However, the correlation between flow and suspended solids, which is the difference between total and dissolved solids, is essentially zero. It is thought that this is due to errors incurred by subtracting two large numbers. Unfortunately, this is the parameter which is of interest because it is commonly measured by wastewater treatment plants. The only other correlations which may be significant are the .22 correlation between flow and fecal coliform for the Quinnipiac river, and the .35 correlation between flow and BOD for the Wallingford wastewater treatment plant.

References:

Crabtree, R.W., Cluckie, I.D., and C.F. Forstar, "Percentile Estimation Procedures for Water Quality Management", Effluent and Water Treatment Journal, February, 1986.

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Ray, W.C., and W.R. Walker, "Low Flow Criteria for Stream Standards", ASCE Journal of the Sanitary Engineering Division, 94(SA3):507-520, 1968.

U.S. Environmental Protection Agency, "A Statistical Method for the Assessment of Urban Stormwater", EPA 440/3-79-023, 1979A

Warn, A.E., and J.S. Brew, "Mass Balance", Water Resources Research, 14:1427-1434, 1980.

Figure 1

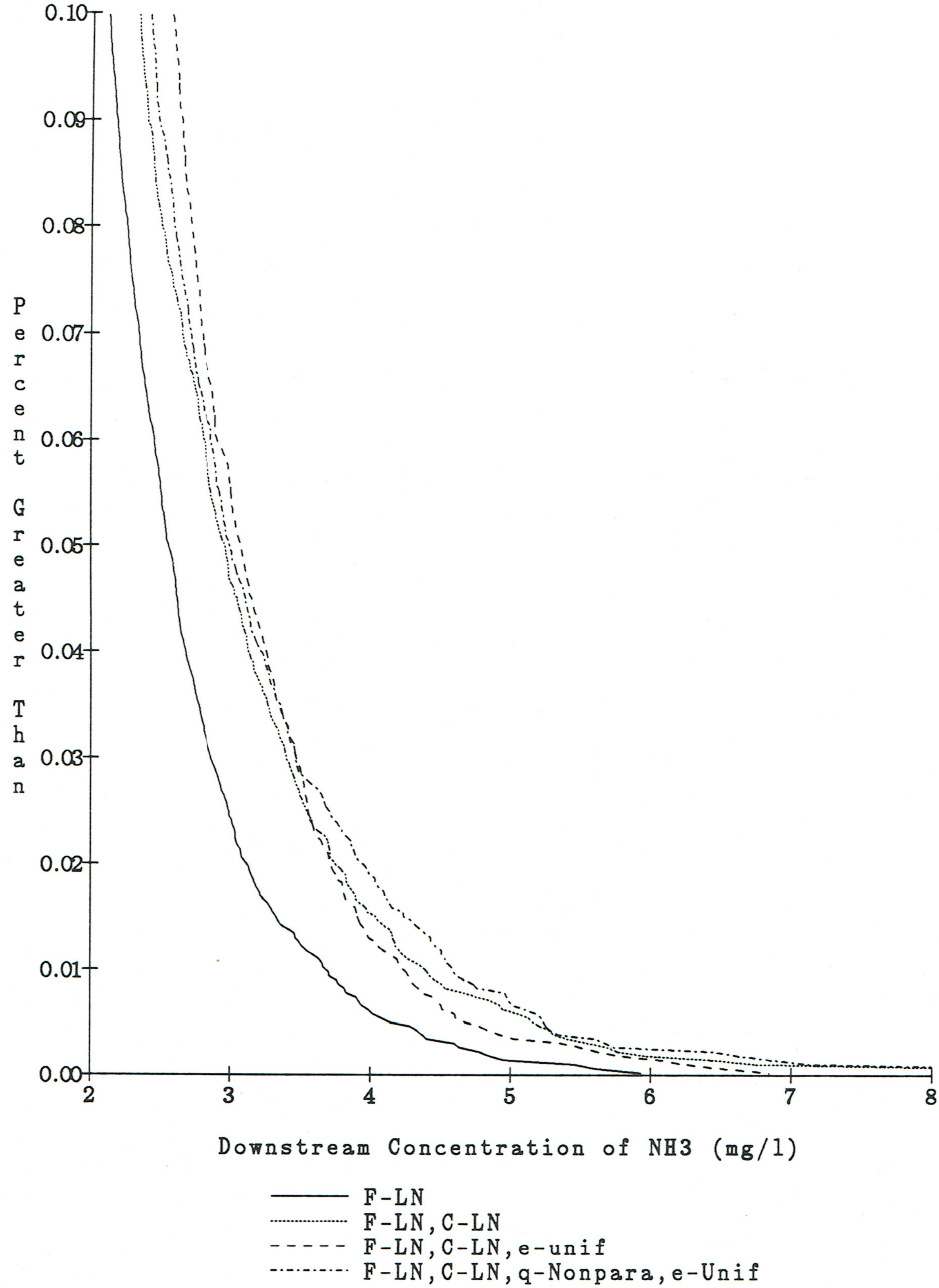
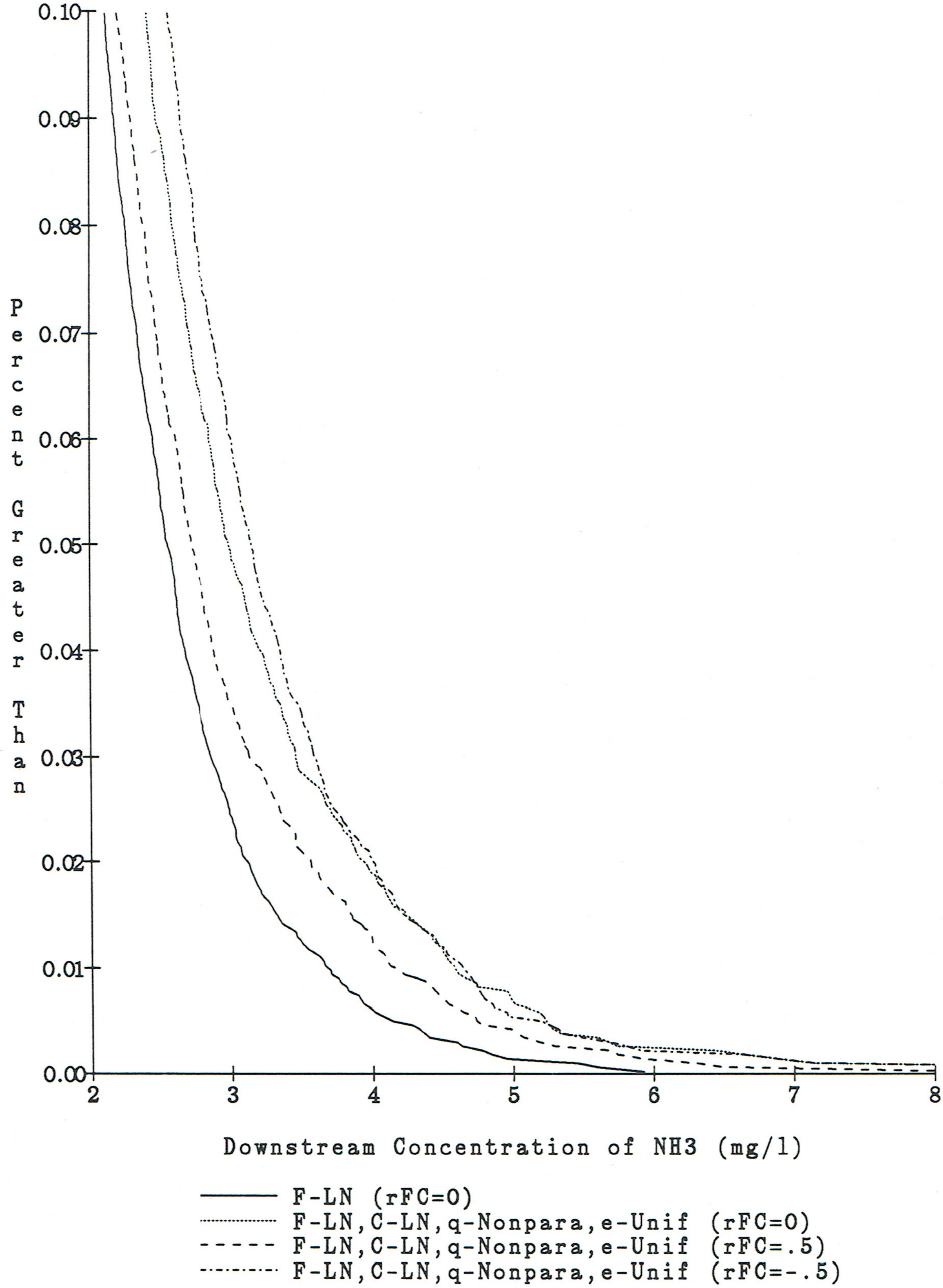

0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Percent Greater Than
2
3
4
5
6
7
8
Downstream Concentration of NH3 (mg/l)
F-LN
F-LN, C-LN
F-LN, C-LN, e-unif
F-LN, C-LN, q-Nonpara, e-Unif

Figure 2



0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Percent Greater Than
2
3
4
5
6
7
8
Downstream Concentration of NH3 (mg/l)
F-LN (rFC=0)
F-LN,C-LN,q-Nonpara,e-Unif (rFC=0)
F-LN,C-LN,q-Nonpara,e-Unif (rFC=.5)
F-LN,C-LN,q-Nonpara,e-Unif (rFC=-.5)

Table 1				
Variable	Best Fit Distribution	Parameters	Arithmetic Mean	Arithmetic Variance
Upstream Flow (F)	Lognormal	mu=5.15+2 sigma=.73706	230.2	42766
Upstream NH3 (C)	Lognormal	mu=-1.1704 sigma=.93654	0.483	[illegible].31
Effluent Flow (q)	Nonparametric		6.8	[illegible]
Effluent NH3 (e)	Uniform	min=11.838 max=25.033	18.4	14.[illegible]

Table 2: Moment Approximation Method*

Variable	Arithmetic Average	Variance Arithmetic	Coefficient Variation	Log Mean	Log Stand. Deviation
C (mg/L)	0.48309	0	1.152	-1.150	0.919
F (cfs)	230.18	42766	0.898	5.143	0.[illegible]
e (mg/L)	18.435	15	0.207	2.893	0.204
q (cfs)	6.8	1	0.120	1.910	0.120
D				3.233	0.778
phi	0.048	0.002	0.852	-3.317	0.[illegible]
T (mg/l)	1.3		0.697	0.093	[illegible]

Percentiles

alpha	0.0288	0.9712
z	-1.899	1.899
phi (alpha)	0.0089	0.1475
T (alpha)	0.33	3.63

* Adapted from DiToro (1984)

Table 3: Correlations for Quinnipiac River

	Flow	Tot Sol	Fec Col	Dis Sol	Sus Sol	TON
Tot Sol.	-0.719					
Fec Col.	0.221	-0.201				
Dis. Sol	-0.709	0.867	-0.154			
Sus. Sol	-0.008	0.208	-0.15	-0.272		
TON	-0.13	0.155	-0.29	0.123	-0.009	
NH3	-0.096	0.24	0.053	0.195	0.1	-0.105

Table 4: Correlations for Wallingford Treatment Plant

	BOD	Total Suspended Solids	NH3
Flow	0.347	0.132	0