DATE: 8/10/99

MEMO TO: Linda Logan

CC: Brian Pippen, Ken Ludwa, Paul Fendt

SUBJECT: Alternative Dilution Modeling Procedures Potentially Applicable to Port of Seattle Storm Water Outfalls

Summary

This memo summarizes my review of the data and regulatory guidance documents that I was provided concerning the evaluation of the reasonable potential for exceedence of State water quality standards (WQS) at the proposed storm water outfalls. This review identified three alternative methods that could potentially be useful to determine compliance. The parameters and calculation procedures for these methods are listed in the accompanying three tables shown as attachments.

The first method is based on an internal Ecology position paper, and later guidance provided in Ecology's Permit Writer's Manual (last updated in July 1998). It is basically a single event (static) evaluation that requires determination of parameters from probability-exceedence relationships that have to be determined for the site. The exceedence levels, e.g. the 95th percentile effluent pollutant concentration, is stipulated in the Permit Writer's Manual (Chapter VI Water Quality Based Effluent Limits for Surface Water). The steps that are required to complete this method are shown in Table 1. The HSPF simulation results that have been developed could be used to calculate the probability-exceedence relationships needed for this method. A graphical plot of annual series data obtained from the output of ANNIE (or SWDM), the data management program used with HSPF, is the easiest approach to obtain the values needed to calculate dilution factors. The dilution factors are used along with ambient and effluent pollutant concentrations to obtain an estimate of receiving water pollutant concentration to compare against the WQS.

The second method is basically a dynamic (continuous) simulation approach. Ecology (Permit Writer's Manual) provides an option to use this approach. This is the approach that Bill Fox has used for wastewater dilution analyses to argue the single event method is too conservative. The continuous simulation approach that Brian Pippin and Lisa Martin have developed thus far considers the hourly hydrologic simulation results from the HSPF models. The steps required to complete this method are shown on Table 1. In taking this method to the next step, I would include the volumetric limitation to the dilution factor (DF) shown in the equations for DF's shown on the attachments. Essentially, this method will require computing the one-hour (acute boundary) and 96-hour average (chronic boundary) DF's for the period of record, calculating the estimated pollutant concentrations for these DF", and summing joint probabilities to obtain the marginal probability distribution. As Table 1 indicates, the acute boundary conceptual DF's (unadjusted for WAC volumetric limitations) have been completed.

A third method is one that has been funded and developed by the EPA. It's based on a probabilistic approach that is described in a paper, "Probability Model of Stream Quality Due To Runoff" (Dominic Di Toro, *ASCE Journal of Environmental Engineering*, VOL. 110, June 1984). EPA contracted with Versar Environmental Risk Management, Inc. to develop a computer program to implement this method on a national level. I obtained a copy of the computer program documentation. The program contains USGS streamflow data for the major river basins with the continental U.S. It also can be applied to ungaged streams if the mean and low flow (7Q10) streamflow can be estimated. A potential problem with the computer program (but not the methodology) is that the ambient background concentration of the pollutant of interest is assumed zero to simplify the calculation requirements. I spoke to the one of the program developers at Versar who indicated at the time it was developed, EPA was not concerned about background concentrations. However, the basic methodology by Di Toro does not require this simplification. I've included an excerpt from the paper that shows an example applied to a stream that has a background concentration for the pollutant. This methodology could be easily solved using the EXCEL spreadsheet or other statistical program that handles time series calculations. The estimated pollutant concentration for Ecology's exceedence level criteria could be determined from the calculation procedure.

Discussion Topics

As Table 1 indicates, it would be relatively easy to continue using the continuous simulation method and complete the reasonable potential determination. The additional work that would be needed is to develop the statistics for the chronic dilution boundary, and perform the calculations to obtain the probability distributions for the pollutants for both dilution zone boundaries.

Alternately (or in conjunction) with this method, one of the other methods could be used to compare the evaluation results. The benefits to be gained from using an additional might include some validation for the results of the continuous simulation approach relative to agency promulgated guidance, and the method might show the relative conservatism of the (method 1) guidance if the water quality data indicates the probability distribution of the high pollutant concentrations is low.

Some considerations relative to whether to proceed that have occurred to me include:

1. What are the client's expectations?
2. What has been Ecology's involvement to date and their receptivity to or recommendations concerning how to evaluate the potential issues?
3. What do the ambient and effluent water quality data exceedence probability distributions look like, and is background concentration an issue?
4. How much budget is available to complete the work?

TABLE 1. ADDITIONAL ANALYTICAL TASKS

PARAMETER	METHOD 1 DOE SINGLE EVENT MODEL	METHOD 2 CONTINUOUS SIMULAT. MODEL	METHOD 3 EPA PROBABILISTIC MODEL
METALS WATER QUALITY STDS	DETERMINE LOWEST HARDNESS FROM DATA; CALCULATE ACUTE/CHRONIC CRIT.	→	→
AMBIENT FLOW	USE ANNIE (SWM) TO CALC/PLOT 1&30 DAY LOWEST ANNUAL SERIES FLOW FREQ; USE PROGRAM TO DELETE JUNE, JULY, CALC/PLOT 30 DAY LOWEST ANNUAL	USE FORTRAN PROGRAM TO CALC 96-HOUR MOV AVG FOR CHRONIC DILUTION 1-HOUR FOR ACUTE (COMPLETED)	SEE DI TORO Example
EFFLUENT FLOW	USE PROGRAM TO CALC 6 & 72 HOUR AVERAGE FLOWS. CALC & PLOT LOGNORMAL PROB - PEAK FLOW DISTRIBUTIONS	"	"
MAXIMUM AMBIENT CONCENTRATION	CALCULATE / PLOT LOGNORMAL PROB- CONCENTRATION DISTRIBUTIONS	ASSUME 90th PERCENTILE FROM DISTRIBUTION OR CALCULATE FLOW-CONCENTRATION RELATIONSHIP	"
MAXIMUM EFFLUENT CONCENTRATION	CALCULATE / PLOT LOGNORMAL PROB. CONCENTRATION DISTRIBUTIONS	"	"

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METHOD 1 - DETERMINATION OF REASONABLE POTENTIAL

BASED ON DOE POSITION PAPER & PERMIT WRITERS MANUAL

PARAMETER	ACUTE DILUTION	CHRONIC DILUTION
METALS WQS:	≤ 1 EXCEEDANCE/HOUR EVERY 3 YEARS; P=0.33 $Cu \leq (0.960)(e^{(0.9422[\ln(Hardness)]-1.464)})$	≤ 1 EXCEEDANCE / 96 HOURS EVERY 3 YEARS; P_A=0.33 $Cu \leq (0.960)(e^{(0.9422[\ln(Hardness)]-1.465)})$
AMBIENT "CRITICAL" CONDITION (QA)	LOWEST DAY W/ 3-YR RECURRENCE INT. ANNUAL SERIES	LOWEST MONTHLY AVERAGE W/ 3-YR RECURRENCE INT. FROM PARTIAL (AUG-MAY) SERIES (JUNE & JULY EXCLUDED)
EFFLUENT "DESIGN" DISCHARGE (QE)	PEAK 1-HOUR IN 6-HOUR FOR 2-YR$_{RI}$ EVENT FROM ANNUAL SERIES	AVERAGE 72-HOUR FOR 2-YR$_{RI}$ EVENT FROM ANNUAL SERIES
MAXIMUM AMBIENT CONCENTRATION (MECB)	# DATA POINTS <20: GM x 1.74 >20: LOGNORMAL PROB DIST. 90th PERCENTILE (IF DATA ARE CRITICAL SEASON)	SAME AS ACUTE
MAXIMUM EFFLUENT CONCENTRATION (MEC)	USE TRANSLATOR → TOTAL DISSOLVED METAL # DATA POINTS <20: C.V. * POINTS ⇒ MULTIPLIER FROM EPA Table 3-2 X HIGHEST VALUE >20: LOGNORMAL PROB DIST. 95th PERCENTILE	SAME AS ACUTE
CALCULATION PROCEDURE:	EVENT BASED - SINGLE VALUE EVALUATION $CP_{AC} = ((MEC * TRANSLATOR) + MECB*(DF_{AC}-1))/DF_{AC}$ $DF_{AC} = ((QA * 0.025) + QE)/QE$	EVENT BASED - SINGLE VALUE EVALUATION $CP_{CH} = ((MEC * TRANSLATOR) + MECB*(DF_{CH}-1))/DF_{CH}$ $DF_{CH} = ((QA * 0.25) + QE)/QE$

COMPARE SINGLE VALUE RESULTS TO WQS TO EVALUATE COMPLIANCE

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METHOD 2 – DETERMINATION OF REASONABLE POTENTIAL

BASED ON CONTINUOUS HYDROLOGIC (HSPF) SIMULATION

PARAMETER	ACUTE DILUTION	CHRONIC DILUTION
METALS WQS:	≤ 1 EXCEEDANCE / HOUR EVERY 3 YEARS; $P_A = 0.33$ CU (see DOE)	≤ 1 EXCEEDANCE / 96 HOURS EVERY 3 YEARS; $P_A = 0.33$ CU (see DOE)
AMBIENT CRITICAL CONDITION DISCHARGE (QA)	48 YEARS – 1 HOUR HSPF SIMULATION RESULTS FOR STREAM	48 YEARS – MOVING AVERAGE 96 HOUR HSPF SIMULATION RESULTS FOR STREAM
EFFLUENT "DESIGN" CONDITION DISCHARGE (QE)	48 YEARS – 1 HOUR HSPF SIMULATION RESULTS FOR OUTFALL	48 YEARS – MOVING AVERAGE 96 HOUR HSPF SIMULATION RESULTS FOR OUTFALL
MAXIMUM AMBIENT CONCENTRATION (MECB)	95th PERCENTILE OF f_d TSS < 11.4 mg/L – 1 mg/L TSS > 11.4 mg/L – $2.29 * TSS^{-0.341}$ USE TRANSLATOR → TOTAL DISSOLVED	SAME AS ACUTE
MAXIMUM EFFLUENT CONCENTRATION (MEC)	PEAK MAXIMUM 1 HOUR DOES DATA EXIST TO SHOW RELATIONSHIP TO EFFLUENT DISCHARGE?	MOVING AVERAGE 96 HOUR SAME QUESTION (ACUTE) APPLIES TO CHRONIC
CALCULATION PROCEDURE FOR CONC. OF POLLUTANT (CP)	$CP_{AC} = ((MEC_{AC} * TRANSLATOR) + MECB * (DF_{AC} - 1)) / DF_{AC}$ WHERE $DF_{AC} = ((QA * 0.025) + QE) / QE$	$CP_{CH} = ((MEC_{CH} * TRANSLATOR) + MECB_{CH} * (DF_{CH} - 1)) / DF_{CH}$ WHERE $DF_{CH} = ((QA * 0.25) + QE) / QE$
	CONTINUOUS (HOURLY) CALCULATION OF DILUTION & CP	
	PLOT MARGINAL PROBABILITY DISTRIBUTION FOR QA TO EVALUATE COMPLIANCE W/ WQS	

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METHOD 3 - DETERMINATION OF REASONABLE POTENTIAL

PARAMETER	ACUTE DILUTION	CHRONIC DILUTION
METALS USES ..	SAME AS PREVIOUS	SAME AS PREVIOUS
CALCULATION PROCEDURE:	SEE TABLE 1 FROM QUALITY	EXAMPLE CALCULATION OF STREAM PROBABILITY MODEL DOE TO RUNOFF = BY DOMINIC DI TORO

BASED ON DI TORO'S PAPER

which the criteria concentration was exceeded and, presumably, water use was impaired.

Probabilistic water quality analysis attempts to calculate the same output variable probability distributions but without resorting to brute force time variable computation. Instead, the probability distributions and correlation structure of the input variables are used to calculate *directly* the probability distribution of the output variables. In a sense, therefore, the methods are computational simplifications. But, much more important, they are conceptional simplifications. They require only the relevant statistical properties of the input sequence, e.g., medians, coefficient of variations, and cross correlations, which are much easier to quantify and understand than the raw input sequences themselves. Therefore, the problem becomes much more manageable and comprehensible.

Probabilistic methods have been developed in response to a need to understand the results of complex time variable simulations (7,9,12,13,15) that were the only available frameworks for the analysis of the effect of combined and separate sewer runoff into receiving waters. The probabilistic analysis of the response of one dimensional advective-dispersive systems has been reviewed elsewhere (6). The performance of runoff treatment devices have also been analyzed in this way (5,8,14). It is the purpose of this paper to analyze a simple dilution model that appears to be well suited for application to the behavior of substances at locations downstream of the point of complete vertical and lateral mixing but upstream of locations where removal and other mechanisms have a significant impact. The spirit of the analysis is similar to those cited previously. If possible, an analytical or analytical-numerical method is sought that solves an idealized version of the problem. These results provide a screening level of analysis and also contribute to an understanding of the problem without resorting to simulation techniques. Monte Carlo methods can, of course, be used to examine the problem posed in this paper and provide more detailed results with less restrictive assumptions. However, the screening level can rapidly isolate the problem components that warrant that level of analysis, and provide an initial estimate against which to judge and corroborate more detailed calculations.

Problem Framework.—The deterministic model of interest is a simple mass balance at the location where the runoff enters the stream. Let C_R and Q_R be the event mean runoff concentration and flow rate, respectively, for a specific event. Let C_S and Q_S be the mean upstream concentration and stream flow during that event. Then the downstream concentration is given by:

$$C_T = \frac{Q_S}{Q_S + Q_R} C_S + \frac{Q_R}{Q_S + Q_R} C_R \quad \ldots\ldots (1)$$

The probability model to be employed is that C_S, Q_S, C_R and Q_R are jointly lognormally distributed. This is a surprisingly realistic characterization of many streams and runoff data sets (4,13). An example is presented subsequently. It is also mathematically tractable, and this combination makes the lognormal characterization irresistible. It should be pointed out, however, that the realism of this characterization should be checked for each application.

The question to be answered is: For flows and concentrations jointly lognormal with cross correlations as appropriate, what is the probability distribution of C_T? The case during which runoff is occurring is considered first. An approximate (moment) method which gives quite useful results is presented, followed by a more exact, numerical method. These results are then extended to include both runoff and nonrunoff periods to complete the analysis.

Moments Approximation.—An approximate probability analysis of the mass balance equation can be made based upon the first two moments, i.e., the mean and variance, of the downstream concentration (16). If these can be calculated and if it is further assumed that the downstream concentration is lognormally distributed, the problem is solved. The latter assumption follows from the following observations. The mass balance equation can be written as

$$C_T = C_R \phi + C_S (1 - \phi) \quad \ldots\ldots (2)$$

in which $\phi = Q_R/(Q_R + Q_S)$ is the event mean runoff flow fraction. If ϕ and $1 - \phi$ were lognormal, then, since C_R and C_S are assumed to be lognormal, the products $C_R \phi$ and $C_S(1 - \phi)$ would also be lognormal. It is a curious fact that the sums of lognormal random variables have tails which are also approximately lognormal (11).

In any case, these observations suggest that C_T should be approximately lognormal, and the mean and variance suffice to determine its distribution. This approach has been utilized previously by Warn and Brew (16) who show that the arithmetic mean and variance of C_T are given by:

$$\mu(C_T) = \mu(C_R)\,\mu(\phi) + \mu(C_S)[1 - \mu(\phi)] \quad \ldots\ldots (3)$$

$$\sigma^2(C_T) = \sigma^2(\phi)[\mu(C_R) - \mu(C_S)]^2 + \sigma^2(C_R)[\sigma^2(\phi) + \mu^2(\phi)] + \sigma^2(C_S)[\sigma^2(\phi) + (1 - \mu(\phi))^2] \quad \ldots\ldots (4)$$

where it is assumed that both concentrations, C_S and C_R, are uncorrelated with respect to their respective flows, Q_S and Q_R, and, therefore, the runoff fraction, ϕ. This assumption is removed in the next section where the exact distribution of C_T is computed with cross correlations.

If C_T is assumed to be lognormal, then the relationships between the arithmetic moments, $\mu(C_T)$ and $\sigma^2(C_T)$, and the log mean, μ_l, and log standard deviation, σ_l, which are the moments of the natural log of the concentrations, is (16):

$$\mu_l(C_T) = \ln\left[\frac{\mu(C_T)}{\sqrt{1 + \nu^2(C_T)}}\right] \quad \ldots\ldots (5)$$

$$\sigma_l^2(C_T) = \ln[1 + \nu^2(C_T)] \quad \ldots\ldots (6)$$

in which $\nu(C_T) = \sigma(C_T)/\mu(C_T)$ is the coefficient of variation. The quantiles of C_T are

$$C_{T_\alpha} = \exp[\mu_l(C_T) + z_\alpha \sigma_l(C_T)] \quad \ldots\ldots (7)$$

which is the concentration that is exceeded with probability $1 - \alpha$, and z_α is the standard normal α quantile.

The problem that remains is to compute the moments of ϕ. Warn and Brew (16) suggest a numerical method. However, since this analysis is approximate, it is of interest to find approximate expressions for these moments as well and reserve the numerical techniques for the evaluation of the exact distribution of C_T. This can be done as follows. The runoff fraction can be expressed as

$$\phi = \frac{Q_R}{Q_R + Q_S} = \frac{1}{1 + \frac{Q_S}{Q_R}} = \frac{1}{1 + D} \quad \ldots\ldots (8)$$

in which $D = Q_S/Q_R$. Since both Q_S and Q_R are lognormal, so also is D. Letting $d = \ln(D)$, it is straightforward to calculate the α-quantile of ϕ. As shown in Appendix I if ϕ_α is such that:

$$\Pr[\phi < \phi_\alpha] = \alpha \quad \ldots\ldots (9)$$

$$\text{then:} \quad \phi_\alpha = \frac{1}{1 + \exp[\mu_l(D) - z_\alpha \sigma_l(D)]} \quad \ldots\ldots (10)$$

$$\text{in which} \quad \mu_l(D) = \mu_l(Q_S) - \mu_l(Q_R) \quad \ldots\ldots (11)$$

$$\sigma_l^2(D) = \sigma_l^2(Q_S) + \sigma_l^2(Q_R) - 2\sigma_l(Q_S)\sigma_l(Q_R)\rho_l(Q_S, Q_R) \quad \ldots\ldots (12)$$

$\rho_l(Q_S, Q_R)$ is the cross correlation coefficient between $\ln(Q_S)$ and $\ln(Q_R)$, and z_α = α-quantile of a standard normal random variable, e.g., for $\alpha = 0.95$, $z_\alpha = 1.645$.

The idea is to assume that ϕ is approximately lognormal. Since $\phi = 1/(1 + D)$ and $D = Q_S/Q_R$ is lognormal, if D is large relative to one, then ϕ would be lognormal as well. The suggested approximation is to assume ϕ is lognormal in all cases so that:

$$\ln(\phi_\alpha) = \mu_l(\phi) + z_\alpha \sigma_l(\phi) \quad \ldots\ldots (13)$$

with $\mu_l(\phi)$ and $\sigma_l(\phi)$ as the log mean and standard deviation. This equation makes the connection between the exactly known quantiles, Eq. 10, and the required two moments of ϕ: $\mu_l(\phi)$ and $\sigma_l(\phi)$. To generate two equations for the two unknowns, require that Eq. 13 apply exactly at the α and $1 - \alpha$ quantiles. The result is

$$\mu_l(\phi) = \frac{1}{2}[\ln(\phi_\alpha) + \ln(\phi_{1-\alpha})] \quad \ldots\ldots (14)$$

$$\sigma_l(\phi) = \frac{1}{2z_\alpha}[\ln(\phi_\alpha) - \ln(\phi_{1-\alpha})] \quad \ldots\ldots (15)$$

since $z_{1-\alpha} = -z_\alpha$. It seems reasonable to choose $z_\alpha = 1.645$ to force agreement at the 5% and 95% quantiles.

Once the log mean and standard deviation are calculated from Eqs. 14 and 15, then the arithmetic moments follow from the lognormal assumption:

$$\mu(\phi) = \exp\left[\mu_l(\phi) + \frac{1}{2}\sigma_l^2(\phi)\right] \quad \ldots\ldots (16)$$

$$\nu^2(\phi) = \exp[\sigma_l^2(\phi)] - 1 \quad \ldots\ldots (17)$$

TABLE 1.—Example Calculation[a]—Moments Method

Variable x (1)	Arithmetic average $\mu(x)$ (2)	Median $\hat{x}$ (3)	Coefficient of variation $\nu(x)$ (4)	Log mean $\mu_l(x)$ (5)	Log standard deviation $\sigma_l(x)$ (6)
C_S (mg/L)	325	158	1.8	—	—
Q_S (cfs)	104	90.5	0.567	4.51	0.528
C_R (mg/L)	3,689	2,760	0.887	—	—
Q_R (cfs)	17.5	12.6	0.960	2.53	0.808
D (Eqs. 11–12)	—	—	—	1.97	0.965
ϕ (Eqs. 14–18)	0.148	—	0.973	−2.25	0.816
C_T (Eqs. 3–6)	822	—	1.18	6.27	0.935

Percentiles

	α	0.05	0.95		
	z_α	−1.645	1.645		
	ϕ_α (Eq. 10)	0.277	0.405		
	$C_{T\alpha}$ (Eq. 7)	114	2,472		

[a]All calculations are reported to three significant digits. Median and coefficient of variation of C_S, Q_S, C_R, Q_R are exact as shown. Log cross correlation $\rho_l(Q_S, Q_R) = 0$.

[b]Calculation sequence is: σ_l for Q_S, Q_R (Eq. 6); $\mu_l(D)$, $\sigma_l(D)$ (Eqs. 11–12); ϕ_α for $\alpha = 0.05$, 0.95 (Eq. 10); $\mu_l(\phi)$, $\sigma_l(\phi)$ (Eqs. 14–15); $\mu(\phi)$, $\nu(\phi)$ (Eqs. 16–17) and $\sigma(\phi) = \mu(\phi)\,\nu(\phi)$; $\mu(C_T)$, $\sigma(C_T)$ (Eqs. 3–4); $\mu_l(C_T)$ $\sigma_l(C_T)$ (Eqs. 5–6); $C_{T\alpha}$ (Eq. 7).

and $\sigma(\phi) = \mu(\phi)\,\nu(\phi)$. These arithmetic moments of ϕ are then used in Eqs. 3 and 4 to compute the arithmetic moments of C_T. An example calculation and the sequence of equations used are given in Table 1. Thus, it is possible to compute the exceedence probabilities of C_T directly, without any recourse of numerical integrations. The accuracy of this entire procedure is examined subsequently. It should be noted that the only cross correlation explicitly considered in the moments method is between $\ln(Q_S)$ and $\ln(Q_R)$. The direct evaluation presented below includes $\ln(C) - \ln(Q)$ correlations as well.

Direct Evaluation of Exceedence Probability.—The probability of C_T exceeding C_T^* can be expressed as a multiple integral of the joint probability density over the values of flows and concentration for which $C_T > C_T^*$. This requires an integral for each of the variables C_R, Q_R, C_S, Q_S. One integral can be eliminated immediately by using $D = Q_S/Q_R$ so that:

$$\Pr[C_T > C_T^*] = \Pr\left\{\frac{C_R}{1 + D} + \frac{C_S D}{1 + D} > C_T^*\right\} \quad \ldots\ldots (18)$$

Since Q_S and Q_R are both lognormal, so also is D. For a fixed C_T^* the equality:

$$C_T^* = \frac{C_R}{1 + D} + \frac{C_S D}{1 + D} \quad \ldots\ldots (19)$$

defines a surface in C_R, C_S, D space and the required probability is the