

CHAPTER 188

PREDICTION OF POLLUTANT DISTRIBUTION IN ESTUARIES*

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ABSTRACT

A method was developed for predicting the distribution of sewage constituents which would result from a proposed sewage outfall in estuaries or coastal seas. The method is based on the mathematical relationship between the solutions of the mass-balance equations with and without a decay term and on the assumption that both the dispersion and decaying processes are linear, acting independently. The application of the method requires dye dispersion experiments and a numerical model employing the results of the experiments. This approach makes it possible to predict the concentration field of sewage constituents with differing decay rates by using tracer release experiment employing a conservative tracer.

The method has been applied to assess the environmental impact of a proposed sewage outfall in Hampton Roads, Virginia. Two dye dispersion experiments were performed, one a continuous release over a flood tide cycle and the other over an ebb tide cycle. Horizontal distributions of dye were measured at subsequent slack waters before flood and ebb. The results were used to predict the concentration fields of total nitrogen, total phosphorus, coliform bacteria, biochemical oxygen demand, dissolved oxygen deficit and chlorine residuals, which would result from the proposed sewage outfall.

INTRODUCTION

The dilution and mixing of sewage with receiving water may be considered a two-stage process. The first stage is the initial jet mixing. This initial mixing of the sewage jet with receiving water produces a broad field of diluted sewage. The second stage of mixing is the dispersion of sewage due to natural flow field as the diluted sewage field drifts with the ambient currents.

Models for the first stage, jet mixing, have been studied extensively (Fan, 1967; Fan and Brooks, 1969). These models are capable of delineating the concentration distribution of sewage constituents within the mixing zone.

* Virginia Institute of Marine Science Contribution No. 788.

The layout of diffuser ports, jet momentum, ambient currents and density difference are important parameters affecting the details of the mixing zone.

The second stage of mixing is dominated by the currents and turbulent characteristics of the receiving water. The far field distribution of sewage constituents outside the mixing zone is relatively insensitive to initial mixing. The ideal models for this stage of mixing are based on the equations of motion, continuity and mass balance of sewage constituents (Tracor, 1970). These models calculate the hydrodynamic characteristics, such as currents, density variations, turbulence of receiving water body and use them as inputs to the mass balance equation to calculate the concentration distribution. Due to the amount of field data required for the formulation and verification of this kind of model, it is not always feasible to resort to them for problem solving. Simple models based on the solutions of point or line source in a steady uniform flow field have been developed (Brooks, 1959; Csanady, 1973). The extension of these simple models to an estuarine environment where the flow field is non-uniform and oscillatory, is not straightforward. A purely analytical approach has yet to be developed.

The experimental approach of tracer release has been employed to delineate the far field distribution of pollutant discharge into a water body. Pritchard and Carter (1965) developed a method to estimate the concentration distribution of a nonconservative substance from that of a conservative substance which may be obtained with a field experiment. Their method is based on an empirical relationship that the concentration field of a continuous point source approaches its steady state with an exponential function of time. This paper describes a new approach using the concentration field of a conservative tracer to predict those of sewage constituents discharged from a proposed sewage outfall. This method makes it possible to describe the concentration fields of nonconservative substances without a large field effort to measure or calculate parameters, such as velocity field and dispersion coefficient, which are necessary for solving the mass-balance equation.

THEORETICAL BACKGROUND AND APPROACH

The concentration distribution of a sewage constituent in a receiving water body may be described by the mass balance equation

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} + w \frac{\partial c}{\partial z} = \frac{\partial}{\partial x} (e_x \frac{\partial c}{\partial x}) + \frac{\partial}{\partial y} (e_y \frac{\partial c}{\partial y}) + \frac{\partial}{\partial z} (e_z \frac{\partial c}{\partial z}) - kc + S(x, y, z, t) \quad (1)$$

where

c is the concentration of sewage constituent,
 t is time,
 x, y, z are three orthogonal coordinates,
 u, v, w are velocity components,
 e_x, e_y, e_z are turbulent diffusion coefficients,
 k is decay rate,
 S(x, y, z, t) is source or sink.

As it was stated previously, an ideal model would be the one based on the solution of equation (1) with the velocity components, turbulent diffusion coefficients, decay rate, and source as input parameters. The velocity field and diffusion coefficients have to be solved with a hydrodynamic model or measured in the field. Because of the efforts involved, developing such a model is often unfeasible.

An alternative way of obtaining the concentration distribution of a sewage constituent is to introduce a tracer at the proposed outfall location and measure the resulting concentration distribution. The release of the tracer should last long enough such that an equilibrium condition is achieved. Furthermore, different tracers have to be used to simulate sewage constituents of different decay rates. This direct experimental method is unfeasible in practice because

- 1) for each group of sewage constituents with a different decay rate, a tracer-release experiment has to be done,
- 2) tracers of a given decay rate cannot always be found.

The approach described here is to construct a simple model based on the relationship of concentration distributions between decaying and non-decaying substances. The experimental results of a non-decaying tracer provide the input data of the model and the concentration distributions of decaying substances are calculated.

The Model for a Steady Flow Field

If $N_0(x, y, z, t, t')$ and $N(x, y, z, t, t')$ are the concentration distributions, at time t , resulting from an instantaneous release at time $t = t'$ of non-decaying and decaying substances respectively, then

$$N(x, y, z, t, t') = N_0(x, y, z, t, t') \exp\{-k(t-t')\} \quad (2)$$

where k is the first order decay rate. In a steady flow field, the functions N and N_0 depend on $t - t'$, while they are independent of the time of release t' , therefore

$$N_0(x, y, z, t, t') = N_0(x, y, z, t-t') \quad (3)$$

and

$$N(x, y, z, t, t') = N(x, y, z, t-t') \quad (4)$$

If a tracer is introduced continuously at a constant rate (unit mass per unit time) for an infinitely long time, an equilibrium concentration field will be reached with

$$C_\infty(x, y, z) = \int_{-\infty}^t N(x, y, z, t-t') dt' \quad (5)$$

Let $\tau = t-t'$, equation (5) may be transformed into

$$C_\infty(x, y, z) = \int_0^\infty N(x, y, z, \tau) d\tau \quad (6)$$

and, substituting equations (2) and (3), it may also be obtained that

$$C_\infty(x, y, z) = \int_0^\infty N_0(x, y, z, \tau) \exp(-k\tau) d\tau \quad (7)$$

Mathematically, equation (7) states that the equilibrium concentration field of decaying substances may be calculated from the results of the tracer release experiment with a non-decaying tracer.

However, it is technically impossible to monitor continuously the history of a time-varying concentration field, $N_0(x, y, z, \tau)$. The continuous release of a tracer may be regarded as a succession of piece-wise continuous release of duration T . Equation (5) may be written as

$$C_\infty(x, y, z) = \sum_{n=1}^{\infty} \int_{t-nT}^{t-(n-1)T} N(x, y, z, t-t') dt' \quad (8)$$

Similarly, equations (6) and (7) become

$$C_{\infty}(x,y,z) = \sum_{n=1}^{\infty} \int_{(n-1)T}^{nT} N(x,y,z,\tau) d\tau \quad (9)$$

and

$$C_{\infty}(x,y,z) = \sum_{n=1}^{\infty} \int_{(n-1)T}^{nT} N_0(x,y,z,\tau) \exp(-k\tau) d\tau \quad (10)$$

If the time interval T is small compared with the time scale of decay, i.e. $1/k$, the decaying factor, $\exp(-k\tau)$, may be approximated by a constant $\exp(-\frac{2n-1}{2} kT)$ with an error less than $(kT)^3$, and equation (10) becomes

$$\begin{aligned} C_{\infty}(x,y,z) &= \sum_{n=1}^{\infty} \int_{(n-1)T}^{nT} N_0(x,y,z,\tau) d\tau \cdot \exp(-\frac{2n-1}{2} kT) \\ &= \sum_{n=1}^{\infty} C_{On}(x,y,z) \exp(-\frac{2n-1}{2} kT) \end{aligned} \quad (11)$$

where

$$C_{On}(x,y,z) = \int_{(n-1)T}^{nT} N_0(x,y,z,\tau) d\tau,$$

has a physical meaning as the concentration field resulting from a continuous release of a non-decaying substance over a time interval from nT to $(n-1)T$ in the past. Thus, the series C_{On} may be obtained from a field experiment in which a tracer is continuously released over a time period T and the concentration fields are measured at subsequent time instants $T, 2T, 3T, \dots, nT$ after the beginning of release. Equation (11) may then be used to calculate the equilibrium concentration field of any sewage constituent with decay rate k .

Extension of the Model to Tidal Estuaries

In the case of a non-steady flow field, the functions $N_0(x,y,z,t,t')$ and $N(x,y,z,t,t')$ not only depend on $t-t'$, but also on t' , the time when the tracers are introduced. The analysis in the previous section cannot be applied. However, the model may be easily extended to a tidal estuary if the flow field in the estuary is assumed periodic.

In estuaries where the tidal propagation dominates the flow field, the advective velocities u, v, w and diffusion

coefficients e_x , e_y , e_z are periodic functions of time. The period of fluctuation, one tidal cycle, may be used as the time unit and functions $N_0(x,y,z,n,n')$ and $N(x,y,z,n,n')$ may be defined as the concentration fields at a particular phase of the n^{th} tidal cycle resulting from instantaneous release at any phase of the n^{th} cycle. Because of periodicity, N_0 and N depend only on $n-n'$, while being independent of n' , thus

$$N_0(x,y,z,n,n') = N_0(x,y,z,n-n') \quad (12)$$

$$N(x,y,z,n,n') = N(x,y,z,n-n') \quad (13)$$

Therefore, the analysis of the previous section is still applicable if the time duration of a piece-wise continuous tracer release T equals a tidal cycle.

Equation (11) gives the equilibrium concentration at a particular phase of tide when the concentration fields are measured at that phase of successive tidal cycles. Of the concentration fields varying with phase of tide, the most significant ones are those at slack water before ebb (SBE) or high water slack and at slack water before flood (SBF) or low water slack because they are the extremes of the tidal excursion.

Let a non-decaying tracer be released continuously over a tidal cycle starting at slack water before ebb and let

$CH_n(x,y,z)$ be the measured concentration field at the n^{th} SBE after release begins,

$CL_n(x,y,z)$ be the measured concentration field at the n^{th} SBF after release begins,

then, according to equation (11), the equilibrium concentration field at SBE may be expressed as

$$CH(x,y,z) = \sum_{n=1}^{\infty} CH_n(x,y,z) \exp\left(-\frac{2n-1}{2} kT\right) \quad (14)$$

Since the concentration fields CL_n are not measured at the same tidal phase when the tracer-release begins or ends, the decaying factor of equation (11) has to be modified. The first concentration field CL_1 is measured at a time when the tracer has been released for only half of the tidal cycle. The average decaying factor is $\exp\left(-\frac{1}{4} kT\right)$. For $n \geq 2$, the

concentration fields CL_n are measured at $(n-1)$ tidal cycles after the mid-time of tracer release. The decaying factor is $\exp\{-(n-1)kT\}$. Therefore, equation (11) is modified to

$$CL(x,y,z) = CL_1(x,y,z)\exp(-\frac{1}{4}kT) + \sum_{n=2}^{\infty} CL_n(x,y,z)\exp\{-(n-1)kT\} \quad (15)$$

In deriving equation (11), the decaying factor $\exp(-k\tau)$ is approximated by a constant $\exp(-\frac{2n-1}{2}kT)$ over the time interval $t = (n-1)T$ to $t = nT$. The error introduced by this approximation may be reduced by shortening the duration of continuous tracer release T . For a tidal estuary, this may be easily achieved by separating the tracer-release into two parts: one continuous release over ebb tide and another continuous release over flood tide. Successive concentration fields at SBE and SBF are measured for both releases and constant decay factors applied to each of the measured concentration fields.

Let

$CHF_n(x,y,z)$ be the concentration field of flood tide release, measured at the n^{th} SBE,

$CHE_n(x,y,z)$ be the concentration field of ebb tide release, measured at the n^{th} SBE,

$CLF_n(x,y,z)$ be the concentration field of flood tide release, measured at the n^{th} SBF,

$CLE_n(x,y,z)$ be the concentration field of ebb tide release, measured at the n^{th} SBF.

then, for a non-decaying substance, the CH_n and CL_n in equations (14) and (15) may be expressed as

$$CH_n = CHF_n + CHE_n \quad (16)$$

$$CL_n = \begin{cases} CLF_{n-1} + CLE_n & n \geq 2 \\ CLE_n & n = 1 \end{cases} \quad (17)$$

The asymmetry of indices in equation (17) arises from the fact that CL_n is the concentration field at slack water before flood while the continuous tracer release is assumed to be from SBE to SBE.

For a decaying substance, different decaying factors are applied to the two parts of CH_n and CL_n , and equations (14) and (15) become

$$CH(x,y,z) = \sum_{n=1}^{\infty} CHF_n(x,y,z) \exp \left\{ - \left(\frac{2n-1}{2} - \frac{1}{4} \right) kT \right\} \\ + \sum_{n=1}^{\infty} CHE_n(x,y,z) \exp \left\{ - \left(\frac{2n-1}{2} + \frac{1}{4} \right) kT \right\} \quad (18)$$

$$CL(x,y,z) = \sum_{n=1}^{\infty} CLF_n(x,y,z) \exp \left\{ - \left(\frac{2n-1}{2} + \frac{1}{4} \right) kT \right\} \\ + \sum_{n=1}^{\infty} CLE_n(x,y,z) \exp \left\{ - \left(\frac{2n-1}{2} - \frac{1}{4} \right) kT \right\} \quad (19)$$

The adjustment of $\frac{1}{4} kT$ and $-\frac{1}{4} kT$ for the decaying factors of concentration fields of half-tidal cycle tracer releases improves the accuracy over a continuous full tidal cycle release.

FIELD EXPERIMENT

The model was used to study the proposed Nansemond Sewage Treatment Plant to be located on the south shore of the James River near the mouth of the Nansemond River. The outfall for this plant would be in Hampton Roads at a point roughly 12,000 feet (3,658 meters) from shore and a depth of 20 to 25 feet (6.1 to 7.6 meters), as shown in figure 1. The depth in Hampton Roads is much smaller than the horizontal dimensions of the water body. Vertical mixing by tidal currents is strong so that, at a location outside of the zone of initial mixing, the vertical variation of water constituent concentrations is negligible when compared with horizontal variations. The vertical homogeneity is especially true in late summer when the density stratification is weak and when the water quality problem is severe. Therefore, the horizontal distribution of concentration fields were measured in the tracer release experiments and vertical homogeneity was assumed. Vertical distribution of dye was measured at several locations during the field experiment and they confirmed the vertical homogeneity.

During the summer of 1974, two dye studies were conducted in Hampton Roads to simulate the release of pollutants during the flood and ebb cycles separately. The dispersion and transport of the dye, Rhodamine WT, were

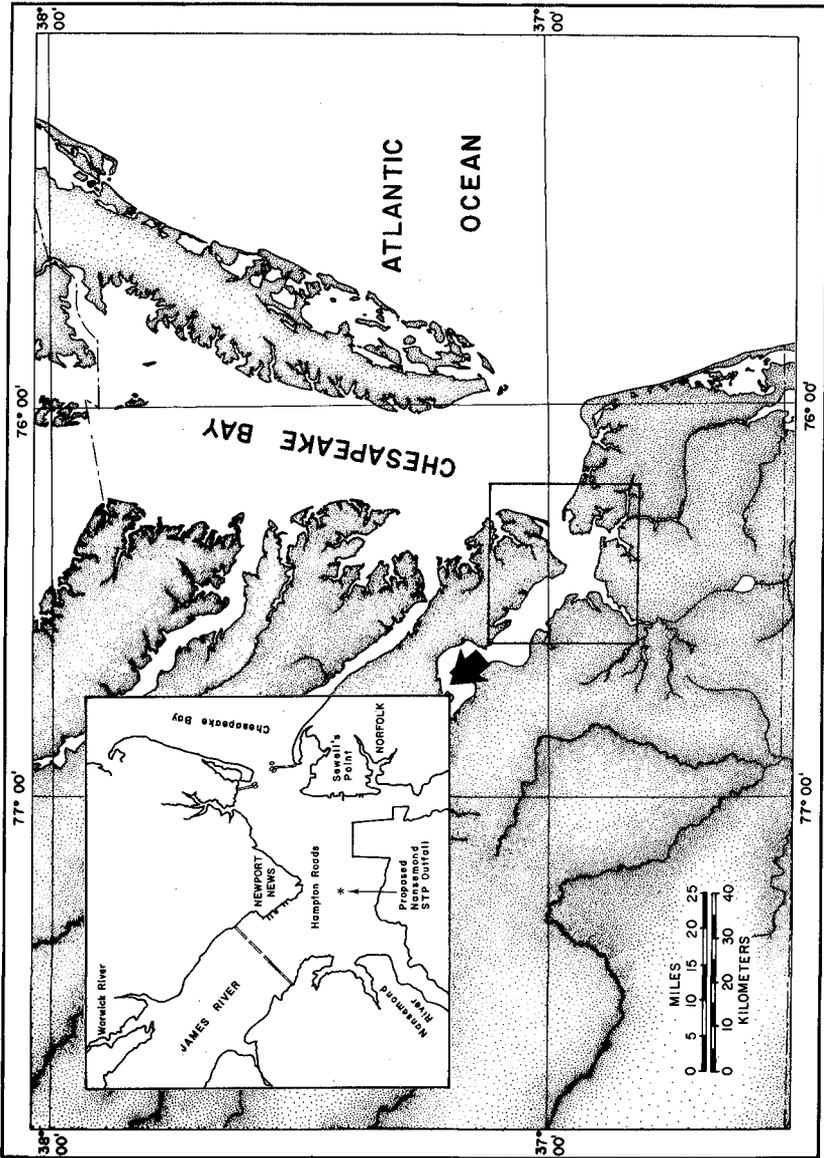
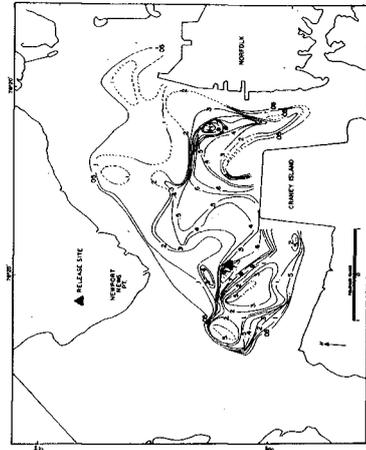


Figure 1. The location map of Hampton Roads and proposed Nansemond STP Outfall.

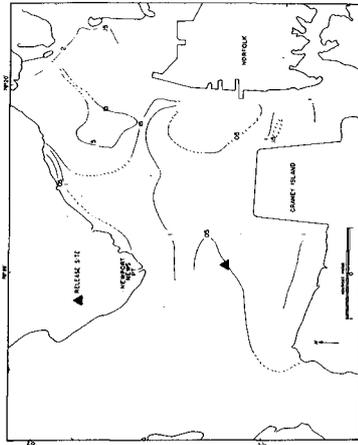
followed for a period of about four days in each experiment. Two moving boats equipped with flow-through fluorometers and Hastings-Raydist navigation units traversed the study area at slack waters before ebb and flood (SBE and SBF). Each boat moved from shore to shore in a zigzag fashion following the period of slack water as it progressed upriver. The near surface (1 ft. or 30.5 cm below surface) dye concentration was monitored continuously and location coordinates were recorded every ten seconds. The data from these cruises were transferred to a chart of the area and contours of equal dye concentration were drawn by hand.

The dispersion and transport of the dye can be seen in figure 2 which shows some samples of dye clouds following the ebb cycle release. No data are presented within the area labeled Initial Mixing Zone, since within that area, there was a significant vertical variation in dye concentration. Outside that area, the concentration was nearly uniform with depth. The initial plume at the first SBF is about six miles long but less than one mile wide (figure 2a). At the following SBE, one complete tidal cycle after the dye release began, the dye cloud reaches from shore to shore, as shown in figure 2b. The dye has been dispersed over a broad area, and the complex pattern of currents in Hampton Roads has broken the dye cloud into several patches. At the second SBF, figure 2c, the dye cloud has been further dispersed and moved downriver. By the fourth SBF, figure 2d, the dye has been dispersed over a large area so that the concentrations are quite low. Much of the dye has left the James and gone into Chesapeake Bay. Similar patterns were found for the dye clouds of the flood cycle release, samples of which are shown in figure 3.

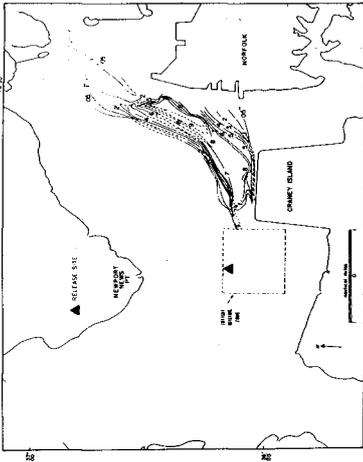
Data from the contours for the various slack waters for both flood and ebb releases were digitized for input to the computer. An 8.5 mile (13.7 kilometer) by 7 mile (11.3 kilometer) grid with 0.1 mile (0.161 kilometer) grid spacing was constructed and dye concentrations at each grid point were tabulated and read into the computer. Due to limited manpower and difficulties surveying at night in an area with a large volume of shipping, it was not possible to sample on every slack tide. Therefore an interpolation procedure was needed to provide the missing data. Values for the dye concentration one tidal cycle prior to and one tidal cycle after the slack with missing data were used to calculate the interim value (Kuo and Jacobson, 1975). Once this procedure had been accomplished, the summation process in equations (18) and (19) was completed and the equilibrium values were printed out on the grid points. This printout was then contoured and the equilibrium distributions were obtained.



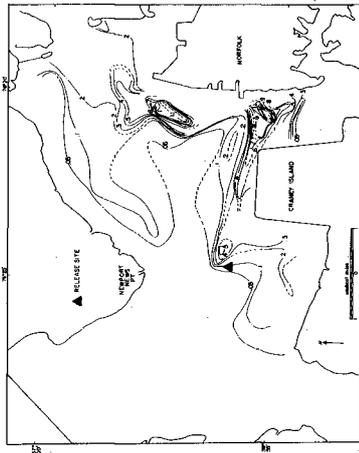
2a 0815, dye concentration in ppb.



2b 0915, dye concentration in ppb.

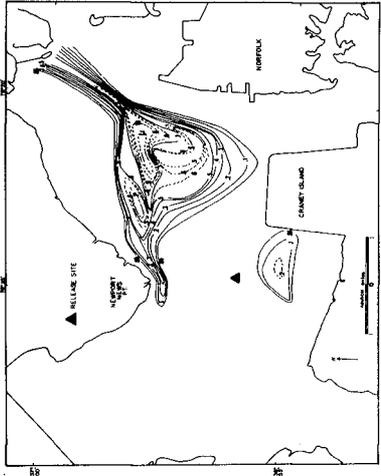


2c 1015, dye concentration in ppb.

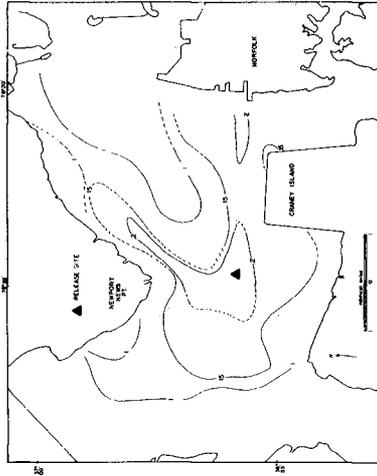


2d 1115, dye concentration in ppb.

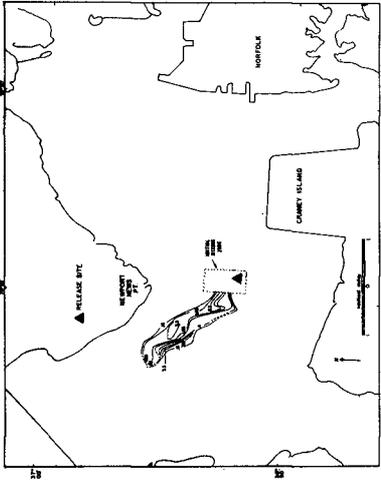
Figure 2. Samples of dye distributions from ebb tide release.



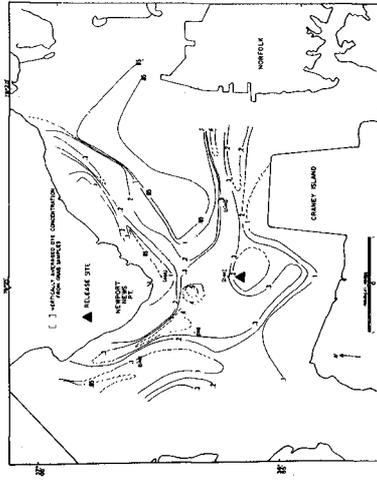
3b cm², dye concentration in ppb.



3d cm², dye concentration in ppb.



3a cm², dye concentration in ppb.



3c cm², dye concentration in ppb.

Figure 3. Samples of dye distributions from flood tide release.

Figure 4 shows the equilibrium concentration fields resulting from a continuous point source of 800 lb/day (363 kg/day). Equations (18) and (19) allow the simulation of the dispersion of nonconservative substances as well as conservative substances. In the figure one can compare the equilibrium concentration distributions for a conservative substance and one with a decay rate of 0.30 per day.

RESULTS

Using the designed effluent loadings of the proposed sewage treatment plant and the dye distribution data from the field experiment, the model was used to predict the distribution of total nitrogen, total phosphorus, biochemical oxygen demand, dissolved oxygen deficit, residual chlorine and coliform bacteria in Hampton Roads. The following are the designed average effluent loadings:

flow	:	16 MGD (0.702 m ³ /sec)
BOD ₅	:	4000 lb/day (1814 kg/day)
total nitrogen	:	25 mg/l (as N)
total phosphorus	:	10 mg/l (as P)
residual chlorine	:	2 ppm
fecal coliform	:	70/100 ml

In the simulation, total nitrogen and total phosphorus were assumed to be conservative substances. The predicted maximum concentrations of total nitrogen and total phosphorus are 40 µg/l and 25 µg/l respectively. Throughout Hampton Roads, concentrations are generally less than 10 µg/l for total nitrogen and 5 µg/l for total phosphorus. The dissolved oxygen deficit was estimated from the equilibrium relationship between reaeration and biochemical oxygen demand (both carbonaceous and nitrogenous). It was concluded that the DO deficit would be of the order of 0.1 mg/l in general, with a maximum of 0.4 mg/l near the initial mixing zone.

The toxicity of residual chlorine resulting from disinfection of treated wastewaters to estuarine organisms has recently been shown to vary widely with the species and the life history stage. For some organisms, e.g. oyster and clam larvae, 48 hours LC50 (50% lethal concentrations) as low as 0.001 ppm have been found (Roberts et al. 1975). In light of these findings and the fact that the James River estuary is the largest producer of seed oysters in Virginia the model was also used to estimate the potential impact of chlorine disinfection on sensitive species in the estuary. This was accomplished by applying the decay rate for chlorine and monochloramine to the field data of dye concentrations. The decay constant utilized was that determined by Bender, et al. (1975) who showed the decay of both chlorine and monochloramine to be approximately first order with $k = 0.05 \text{ hr}^{-1}$. Figures 5a and 5b show the predicted residual chlorine

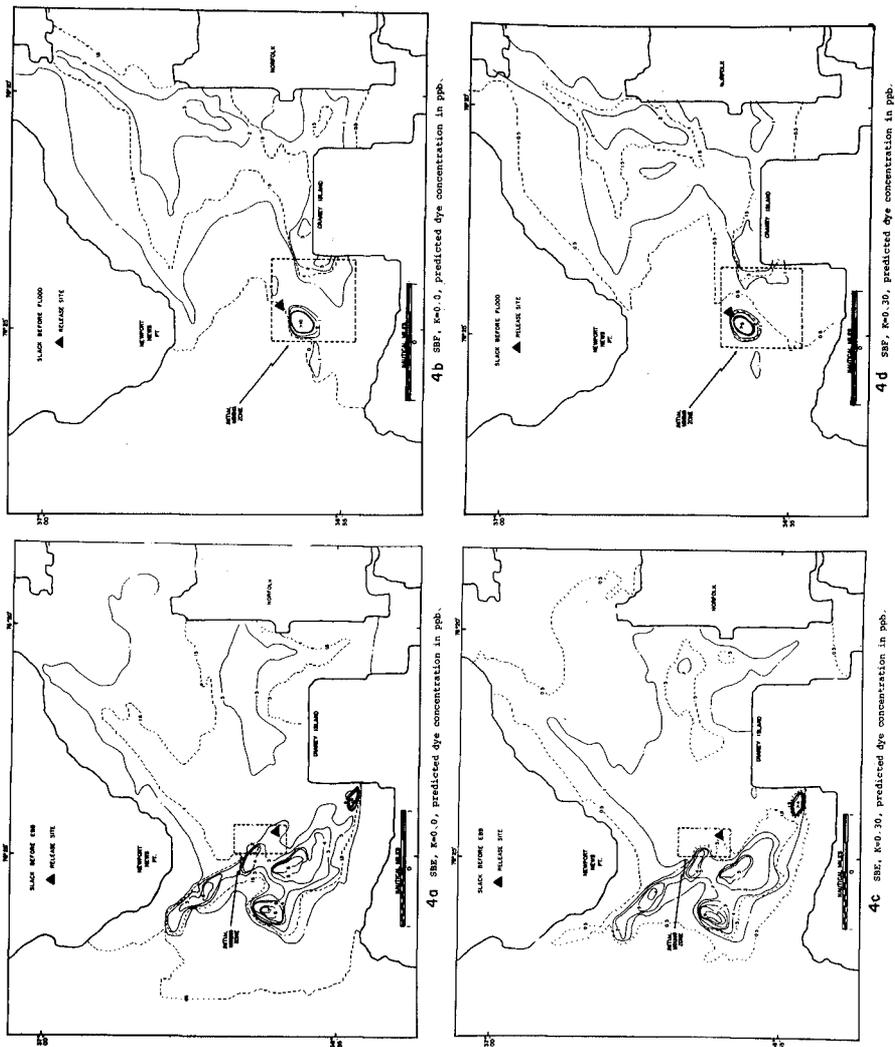
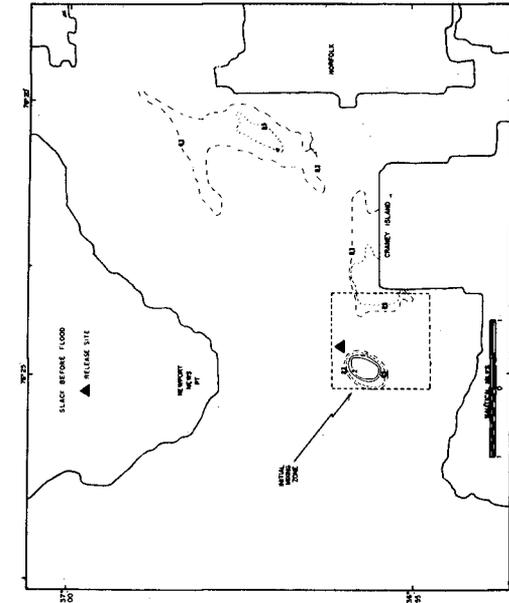
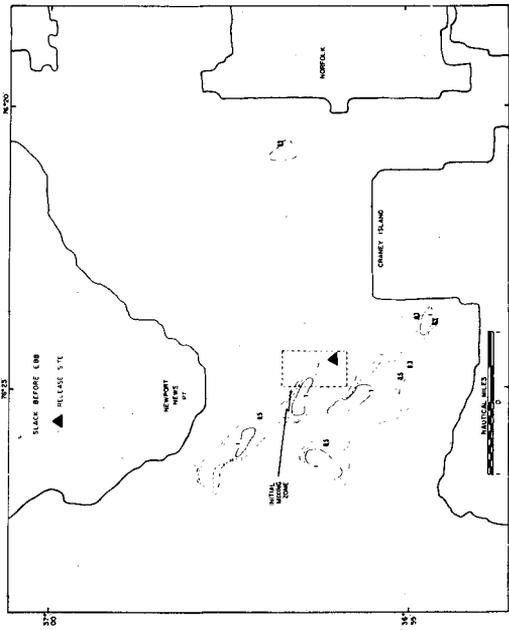


Figure 4. Equilibrium dye distributions from a continuous point source.



5b SBF, predicted chlorine distribution (ppb) for 1995 average loading.



5a SBE, predicted chlorine distribution (ppb) for 1995 average loading.

Figure 5. Concentration fields of residual chlorine.

distributions in the estuary at SBE and SBF respectively. As can be readily seen from inspection of figure 5a, considerable risk to oyster and clam larvae entrained in or passing through this segment seems likely.

Although not directly detrimental to marine organisms, the presence of coliform organisms above given levels in estuarine water is used by public health officials as an indicator of fecal contamination. If coliforms or fecal coliforms exceed accepted limits in a given segment of water the area is restricted for shellfish harvesting, thereby incurring an economic loss of valuable resources without actual damage to the shellfish population.

The model was used to predict the increase in ambient coliform concentrations as the result of proposed effluent loadings. The maximum bacteria level allowable in the effluent was set at 70 fecal coliforms per 100 milliliter of water. The model predicted that the maximum increase in ambient coliform levels was less than 1 per 100 ml. It was concluded that coliform loadings at this rate would not have a detrimental effect from the standpoint of shellfish closures. However, to cover the contingency of a breakdown in normal chlorinating procedures at a sewage treatment plant, an area around a sewage outfall was always designated that no shellfish might be taken within it. The model was used to simulate the coliform distribution which would result from the discharge of unchlorinated secondary effluent (3×10^5 fecal coliform/100 ml) for some specified length of time to simulate the discharge of unchlorinated effluent for finite duration. The summation in equations (18) and (19) was carried out to the first few terms corresponding to the duration of the point source. Figures 6a and 6b show the concentration distributions resulting from chlorination breakdown of half a tidal cycle.

DISCUSSION

The method presented in this paper has three elements: determining the dispersion and transport of a conservative substance released in a water body, some measure of the rate of decay or transformation of the wastewater constituents, and a set of mathematical procedures to combine this information and predict the distribution of nonconservative substances. All three elements will introduce some error. The effluent distributions which have been predicted appear reasonable to the oceanographers who have studied the tidal circulation in this region.

It is possible to note several limitations of the method. First, the determination of the physical dispersion and transport is time and site specific. That is, the results do not apply to other outfall locations nor do they

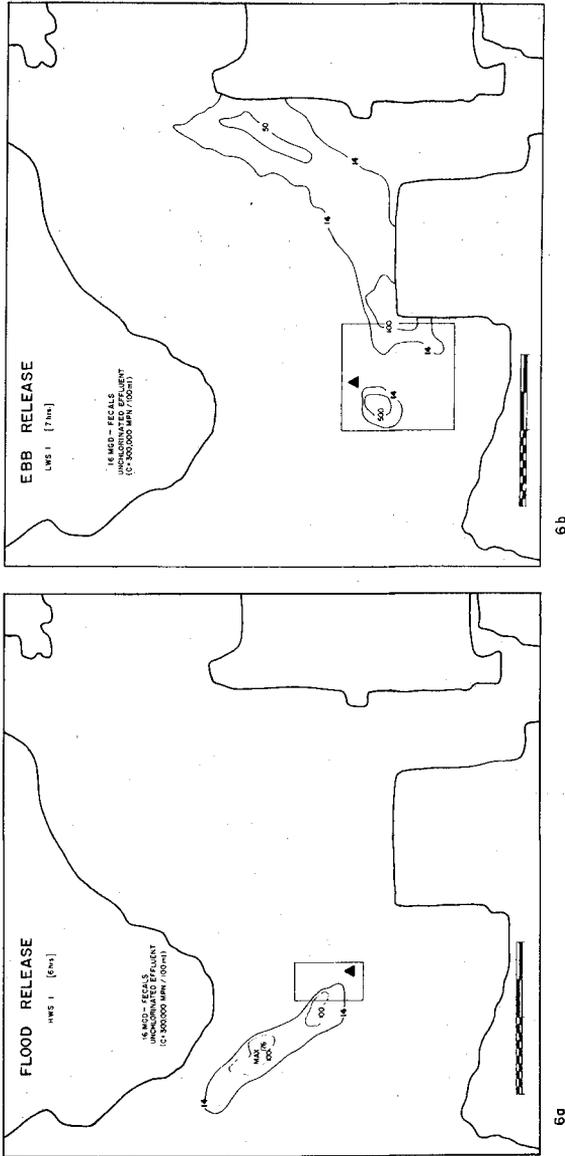


Figure 6. Fecal coliform distributions resulting from unchlorinated sewage.

necessarily apply to other times if the meteorological and hydrographic conditions have changed. An obvious example is that the results of the dye studies conducted in Hampton Roads during the summer of 1974 would not give good predictions for extreme events such as floods or hurricanes. It is not known to what extent the results will be modified when the estuary exhibits strong vertical salinity stratification, as occurs most winters and springs, but it is believed that the results will differ only slightly. If a hydraulic model is available for the water body under investigation, the tests could be repeated for different hydrographic conditions. The results then could be used to give the predictions for the corresponding conditions in the real world.

The rate of decay depends on many biological, geological and chemical processes and it is not always possible to determine a single rate of transformation which will be widely applicable. Therefore, values should be used which underestimate the rate of decay, and therefore provide conservative predictions since the residence time and concentrations will be over-estimated. The errors introduced by the mathematical manipulations are believed to be smaller than those introduced by the other two steps.

ACKNOWLEDGEMENTS

Many thanks are due to our colleagues, especially to Mr. E. P. Ruzecki for his capable supervision of the field study, and to Drs. C. S. Fang and B. J. Neilson for their suggestions and criticism.

This model was developed under the Cooperative State Agencies Program. The continuing support of the Virginia State Water Control Board is appreciated. The application of the model as described herein was supported by Hampton Roads Sanitation District Commission through McGaughy, Marshall & McMillan-Hazen and Sawyer: A Joint Venture. They are appreciated for the financial support and encouragement.

REFERENCES

- Bender, M. E., Roberts, M. H., Diaz, R. and R. J. Huggett, 1975. "Effects of Residual Chlorine on Estuarine Organisms," Proc. Biofouling Workshop, Johns Hopkins Univ., Baltimore, Maryland.
- Brooks, N. H., 1960. "Diffusion of Sewage Effluent in an Ocean Current," Proc. of First International Conf. on Waste Disposal in the Marine Environment, Univ. of California 1959, Pergamon Press, New York.

- Csanady, G. T., 1973. "Turbulent Diffusion in the Environment," D. Reidel Publishing Co., Boston, Mass.
- Fan, Loh-Nien, 1967. "Turbulent Buoyant Jets into Stratified or Flowing Ambient Fluids," W. M. Keck Lab. of Hydraulics and Water Resources Report No. KH-R-15, Calif. Inst. of Tech.
- Fan, Loh-Nien and N. H. Brook, 1969. "Numerical Solutions of Turbulent Buoyant Jet Problems," W. M. Keck Lab. of Hydraulics and Water Resources Report No. KH-R-18, Calif. Inst. of Tech.
- Kuo, A. Y. and J. P. Jacobson, 1975. "A Model for Predicting the Pollutant Distribution from an Outfall in a Tidal Estuary," Spec. Rep. No. 86 in Appl. Mar. Sci. and Ocean Eng., Vol. 5, VIMS.
- Pritchard, D. W. and H. H. Carter, 1965. "On the Prediction of the Distribution of Excess Temperature from a Heated Discharge in an Estuary," Tech. Rep. 33, Chesapeake Bay Inst., The Johns Hopkins Univ., Baltimore, Maryland.
- Roberts, M. H., Diaz, R., Bender, M. E. and R. J. Huggett, 1975. "Acute Toxicity of Chlorine to Selected Estuarine Species," J. of the Fisheries Res. Bd. of Canada, Vol. 32, No. 2.
- Tracor, Inc., 1971. "Estuarine Modeling: An Assessment," EPA, Water Pollution Control Research Series, 16070, DZV 02/71.