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A Tracer Simulation of Waste Transport in the Muddy Creek-Rhode River Estuary, Maryland

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ABSTRACT: A small quantity of Rhodamine WT dye was injected at the headwater of the Muddy Creek estuary and concentration of the dispersed dye was measured with a uniform time interval at a number of fixed locations in the lower portion of the estuary. By the use of the superposition principle of a linear system, the built-up concentration of the dye is found to range from 8 ppb at 1,900 feet downstream from the confluence of the north and south forks of Muddy Creek to 2 ppb near the Smithsonian Institution's pier in the Rhode River, provided that the dye is continuously injected at the headwaters at the rate of one pound per two tidal cycles.

Introduction

The Muddy Creek-Rhode River estuary, Maryland, located about 7 miles south of Annapolis, is a small embayment on the western shore of Chesapeake Bay. Several creeks draining a watershed of approximately 18 square miles feed the shallow 4-square-mile estuary and Muddy Creek, the principal one, drains about one-half of the basin. Most of the land adjacent to the tidal portion of the creek and surrounding the creek's embayment is owned by the Smithsonian Institution's Chesapeake Bay Center for Environmental Studies. The Smithsonian, in conjunction with Johns Hopkins University, the University of Maryland, and various Federal and State agencies, intends to utilize the land area and adjacent water bodies as an experimental area in which to test the principle of ecosystem science.

A small tract of land, 20 acres, and not part of the Center's holdings, lies adjacent to the tidal portion and between the north and south forks of Muddy Creek. A proposal to build 20 or more houses on this tract has been submitted to the Anne Arundel County, Maryland authorities. Because the low topography and shallow water table rule out septic systems, it has been decided that a sewage treatment plant is to be an integral part of the housing development. The plant's effluent will be discharged into the head of the tidal reaches of the south fork of Muddy Creek. Concern about the effects of these discharges motivated the preliminary dye injection study reported here.

A late autumn study was planned in order to show the extreme effects of low freshwater flows. For over a month preceding the test freshwater inflow to the streams feeding the estuary was nonexistent. However, during the test period rainfall did occur and a slight freshwater flow was present in the creek.

Methods and Observations

An amount of 5.7 pounds of dry Rhodamine WT dye was injected near the head of the tidal

portion of the south fork of Muddy Creek at 0715 hours, November 3, 1970. The dye was released at an instantaneous point source 25 minutes prior to high slack water. Ensuing dye movement was monitored by obtaining water samples at a number of predetermined locations in the tidal creek as well as in the Rhode River estuary (Fig. 1). Routine sampling consisted of collecting water samples from a boat at each station at a time interval of about 24.8 hours or two tidal cycles. Sampling was done over a 15-day period terminating November 18 when tracer concentrations at most stations were below detectable limits. Sampling times are indicated in Fig. 2.

In addition to routine sampling, dye movement at early stages of the test was monitored from the boat by water sampling at 3, 6, and 11 hours after the injection and also by visual inspection. The extra monitoring was done for the purpose of obtaining information on the excursion of both the front and the mass center of the dye cloud during one typical tidal excursion from high to low slack water.

The objective of the tracer test was to estimate a potential buildup of concentration of dye by use of the principle of superposition described later. This method requires that water samples be collected at exactly the same locations and at regular time intervals. Almost all samples were collected near the water surface except those collected on November 18, when samples were collected from near the surface and near the bottom. No attempt was made to survey total dye mass balance or lateral and vertical distribution of dye concentrations in a cross section.

The concentrations of Rhodamine WT in water samples were determined by means of a Turner model 111 fluorometer. Temperature of water samples was adjusted to between 23 and 24 C by storage in a constant-temperature bath before analysis. Procedures of the fluorometer analysis followed the method described by Kilpatrick, Martens, and Wilson (written commun., 1970).

Tidal stage data (Fig. 2) were collected continuously by a U.S. Geological Survey water quality monitoring unit installed at the Smithsonian Institution's pier located opposite station 21 (Fig. 1). No other hydraulic data such as velocity and depth were collected during the test; however, *in situ* measurement of surface salinity with a Beckman RB-2

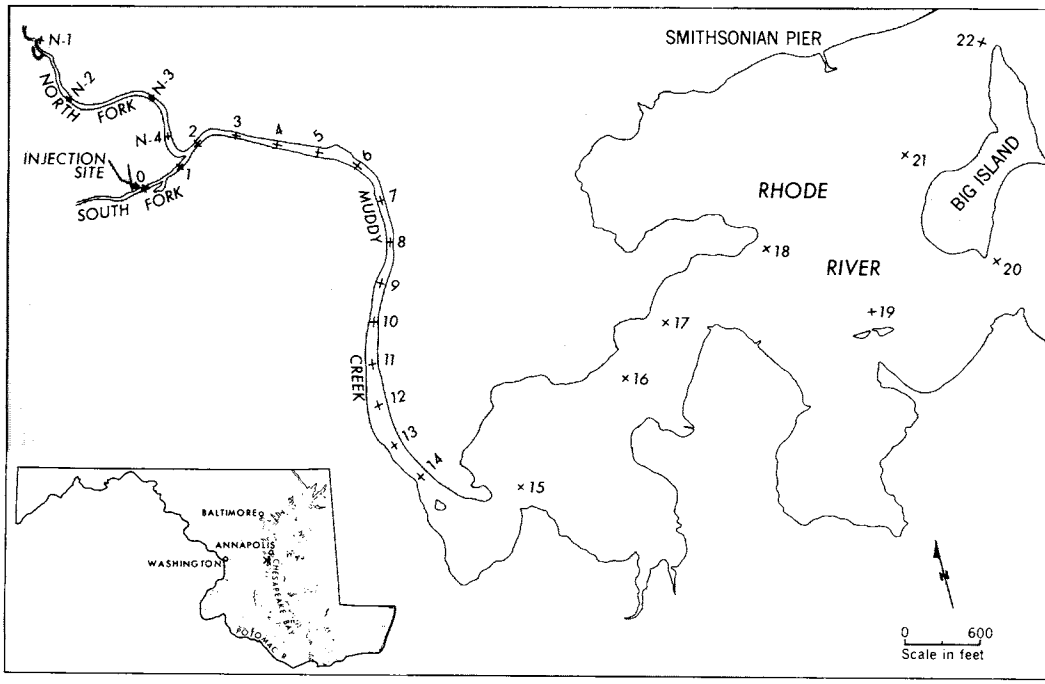

Fig. 1. Map of study area, Muddy Creek-Rhode River estuary, Maryland (Numbers in the map indicate sampling stations)

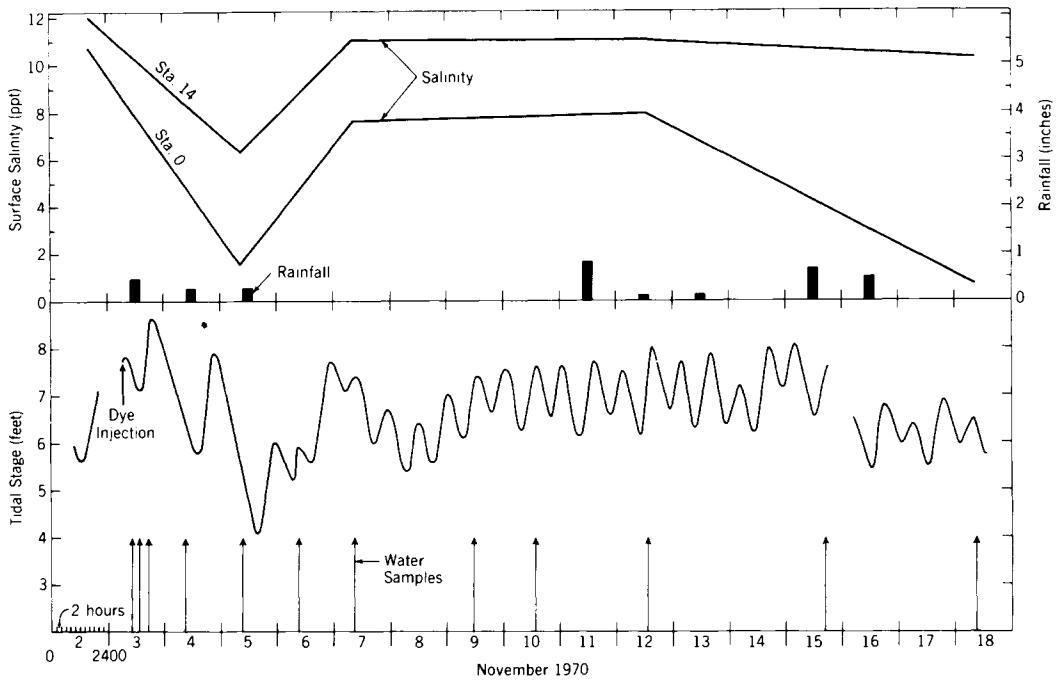

Fig. 2. Time variations of tidal stage, salinity, and precipitation [Salinity is expressed in parts per thousand (ppt)].

salinometer was made at stations 0 and 14 (Fig. 2). The precipitation record in Fig. 2 was obtained from observers at the Smithsonian Institution's Environmental Study Center.

The overall pattern of tracer dispersion is presented in Fig. 3 and the concentration of dye is expressed as parts per billion in weight ratio. At the first low tide, 0.5 tide cycle after the injection (1310 hours, November 3), the center of the dye cloud moved downstream about 2,000 feet from the injection site while the leading edge moved almost to the mouth or 4,500 feet from the injection site. Toward the end of the first tidal cycle (high tide at 1900 hours, November 3), the peak moved upstream in the north fork and was located 1,600 feet upstream from the confluence with the south fork. It is apparent from this observation that, even though the tracer was injected in the south fork, the subsequent movement of the tracer in Muddy Creek was mostly controlled by water movement in the north fork. The tidal excursion during this flood tide was 3,200 feet or more.

Further observation of tidal excursion, however, was curtailed because of the occurrence of extremely irregular tides, which lasted until the end of the 12th tidal cycle (Fig. 2). Thus, even though the peak locations at the end of the second and fourth tidal cycle were observed at 2,200 and 4,600 feet downstream from the confluence, respectively, these movements are not related to an "average" tidal excursion but to the effect of two strong ebb tides which persisted for more than 15 hours each during these sampling periods. These meteorologically induced tides continued ebbing through the predicted times of normal high tide. At the end of the sixth tidal cycle (0900 hours, November 6), however, the dye peak, with each successive high tide, began to move toward the upper end of the north fork of Muddy Creek and remained there for the rest of the observation period. This phenomenon was apparently caused by the rising of tidal stage as well as the reflective effect of the upstream end of the tidal creek.

The behavior of salinity is worth mentioning because it is indicative of the mixing of fresh and saline water in the creek during the test period. At the beginning of the test, salinity gradients in the vertical direction were negligible at all stations and the freshwater inflow was nonexistent. During the long period

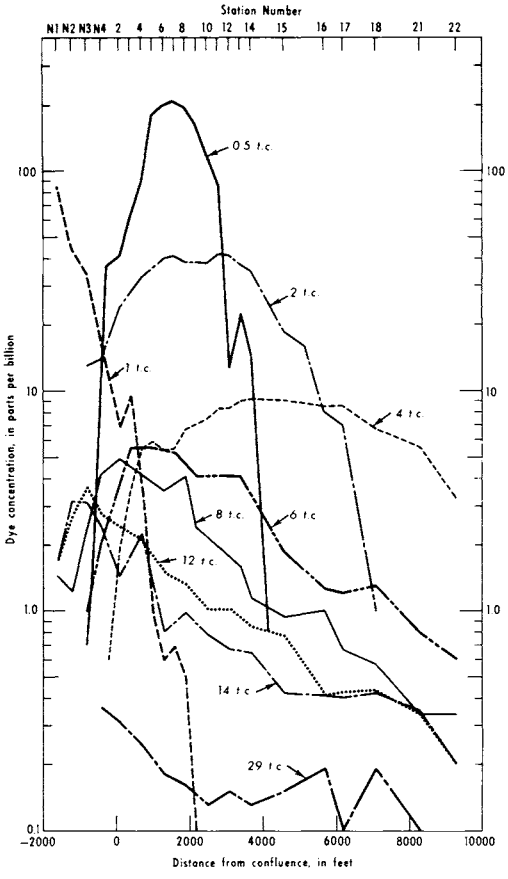

Fig. 3. Longitudinal distribution of observed dye concentration (Abbreviation t.c. designates tidal cycles).

of ebbing tides (November 4, 5, and 6), however, the surface salinity declined sharply at all stations in the creek (Fig. 2), indicating that a large amount of freshwater from rainfall on the day the test began was drawn into the creek because of low levels of the tide stage. As the tide rose back to the normal level at the end of the 8th tidal cycle, some portion of the freshwater moved back to the upstream area while the other mixed with saline water in the creek. Thus, the dye cloud observed at the 2nd, 4th, and 6th tidal periods was exposed to this dilutive mixing in addition to tidal dispersion.

Toward the end of the test, when the tide remained at the normal level, the salinity at station 0 developed a sharp halocline at 1-foot depth in water of overall depth of 3 feet, (0.5 ppt at the surface and 9.6 ppt at the bottom on November 18). It appears that the mass of freshwater due to the precipitation was forming a surface layer without much mixing with the saline water near the bottom. The dye concentrations in the region upstream from station 6 showed that they were much lower than those observed near the bottom indicating that the surface dye concentration was diluted by fresh water. On the other hand, marked freshwater effect could not be detected in the region downstream from station 6. A small gradual halocline was present at station 14 (10.2 ppt at the surface and 11.2 ppt at the bottom on November 18) and no vertical salinity gradient existed at stations 17 and 22. The dye concentrations in the creek downstream from station 6 were higher near the surface than at the bottom and no vertical variation was noticed in the region beyond the confines of the creek. The low dye concentrations near the bottom of the creek appear to be due to the influx of denser bay water into the creek.

Analysis

The basic method used in the estimation of dye concentration buildup in the concerned area is the principle of superposition in a linear system (Bailey, McCullough, and Gunnerson, 1966; and Yotsukura, 1968). It will be assumed that both tides and freshwater discharge return to the same steady condition with a certain time interval, which is a multiple of the tidal cycles, even though the flow within the interval is unsteady. If an additional assumption is made that transport of solutes in such a flow is adequately described by a linear convective diffusion equation, the principle of linear superposition becomes directly applicable to the system. For example, after a single slug injection, a sequence of tracer concentrations observed at specified time intervals at one location can be added together to produce a composite concentration. This calculated concentration represents the concentration that will be built up in the system if slugs of dye were repeatedly and indefinitely added to the system at the specified time interval. In order to simulate a concentration that would result from a continuous uniform injection, it is necessary to spread the initial injection uniformly over the chosen time interval. Another premise accruing from the application

of the principle is that built-up concentrations are linearly related to injection rates.

In estuaries where the complexity of boundary conditions may discourage other approaches such as mathematical or computer simulations the above approach is most useful. The only requirements for the simulation of solute transport by a tracer dispersion test is that a steady flow, with respect to tidal period, exists within the system. The method has been used in several Geological Survey studies in order to estimate waste concentration buildup in estuaries (Hubbard and Stamper, In press; Kilpatrick and Cummings, In press).

Two factors prevented a rigorous application of the above method to the present data. First, the tracer was injected as an instantaneous source over a period of two tidal cycles, the selected interval for data collection. Second, extremely irregular tidal conditions prevailed during the early stage of the test, violating the assumption of steady flow. Nevertheless, the data as a whole were found to be consistent enough to allow for a cautious application of the principle of superposition.

Four stations, 8, 14, 17, and 22, were selected to show changes of dye concentration with respect to time (Fig. 4). As previously stated, prolonged ebb tides at the beginning of the test did not represent "average" tidal conditions. The effects of these tides and also freshwater dilution on dye concentrations were most pronounced upstream of station 8 making the data from those upstream stations unsuitable for the superposition method. Only the data collected at stations downstream from station 8 and after the eighth tidal cycle were considered suitable for superposition analysis.

Another problem was caused by the use of a rather small amount of tracer dye (5.7 lbs.) which resulted in a rapid attenuation of concentration beyond the lower detection limits of the fluorometer. The extrapolation of the data beyond the observation period was done by noting that longitudinal dispersion at these stations for large tidal cycles could be approximated by the one-dimensional equation (see appendix),

$$C = \frac{2M}{A\gamma\sqrt{4\pi KT}}\, e^{-\frac{x^2}{4KT}} \qquad (1)$$

where C is the concentration of a conservative solute in weight ration, M is the amount of solute injected, A is the cross-sectional area, γ is the specific weight of water, K is the longitudinal dispersion coefficient, x is the distance, and T is the time as an n multiple of tidal period t_p($T = nt_p$). The equation is a solution of a diffusion equation

$$\frac{\partial C}{\partial T} = K\frac{\partial^2 C}{\partial X^2} \qquad (2)$$

and applies to the slug injection of a solute at the upstream end of an estuary with constant cross section and having negligible freshwater inflow. If equation 1 is reduced to the form

$$\ln C\sqrt{T} = \ln\left(\frac{2M}{A\gamma\sqrt{4\pi K}}\right) - \frac{x^2}{4KT}, \qquad (3)$$

it is seen that $\ln C\sqrt{T}$ is proportional to $x^2/4KT$ assuming that $\ln (2M/A\gamma\sqrt{4\pi K})$ is constant.

In order to convert observed dye concentration into conservative value, C, it is necessary to start with the equation of dispersion and decay appropriate for the dye, as

$$\frac{\partial C_d}{\partial T} = K\frac{\partial^2 C_d}{\partial X^2} - P_d C_d, \qquad (4)$$

where C_d is the dye concentration and P_d is the decay coefficient for the dye. The dispersion constant K for the dye is assumed to be the same as for conservative solutes and P_d is assumed to depend on time only. The solution to eq. 4 is obtained by means of a transform

$$C_d = Ce^{-\int_0^T P_d dt} \qquad (5)$$

which, when substituted into eq. 4, reduces eq. 4 to eq. 2. In other words, the dye concentration is simply the product of the conservative solute concentration C given by eq. 1 or 3 and the exponential decay term as shown in eq. 5. The ratio, $R = C_d/C$ is plotted against the number of tidal cycles, n, in fig. 5 based on the data from two dispersion tests of Rhodamine WT (Yotsukura, Fischer, and Sayre, (1970), Dyar, Tasker, Waite, and others (1971)). Three different exponential decay rates in the form of $\alpha \exp(-\beta n)$ are used in fig. 5 for the convenience of computation. These are equal to $\exp(-\int_0^T P_d\, dt)$ in eq. 5.

The conservative concentration values thus

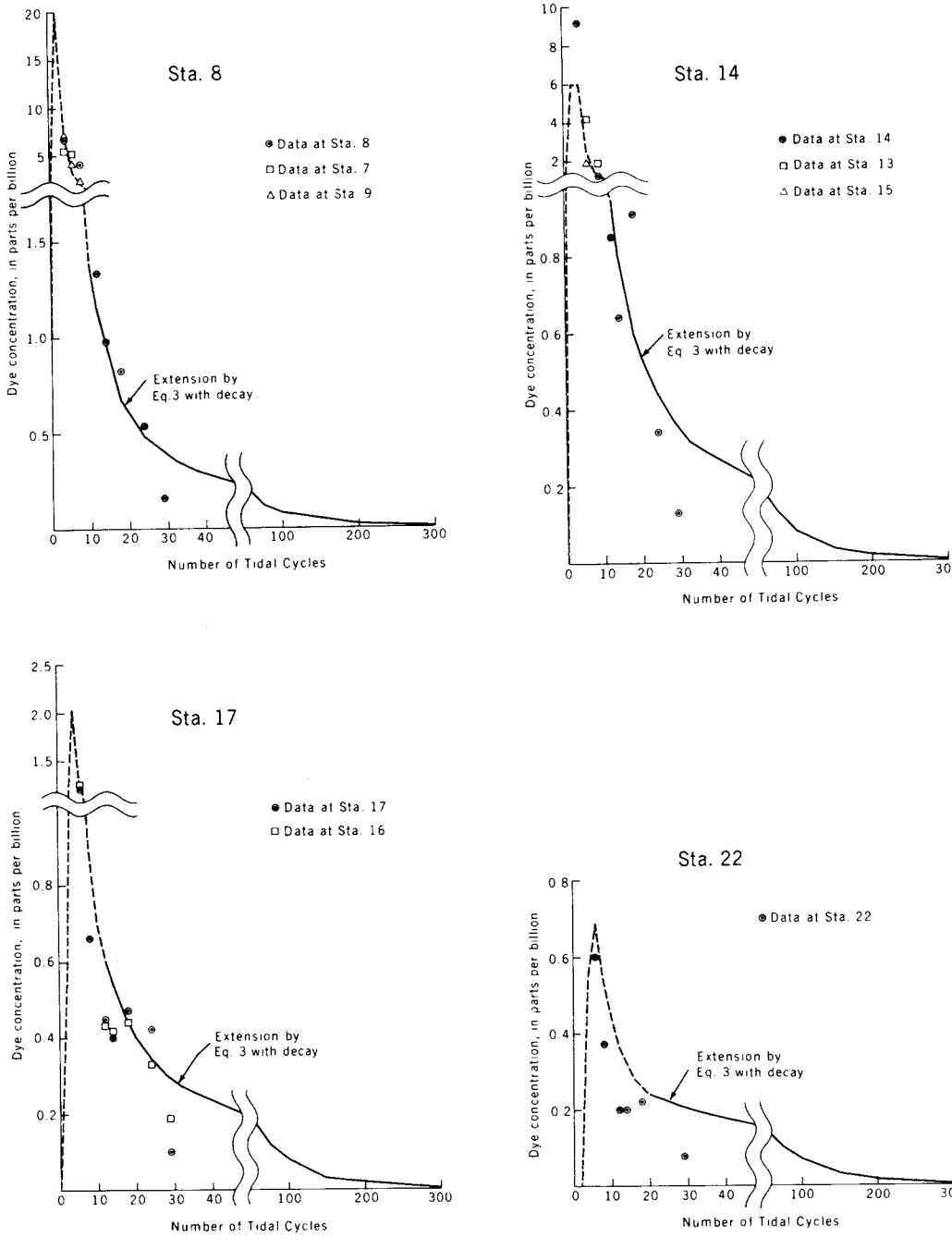

Fig. 4. Time variation of observed dye concentration and its extrapolation at selected stations.

obtained are plotted against distance in Fig. 6, using the variables compatible with eq. 3. Even though the scatter of the data is considerable, the plot shows that the dispersion after the eighth tidal cycle could be described by a straight line representing $K = 25.6$ ft^2 per sec for the reach between stations 8 and 22. The data for the upstream reach show considerable

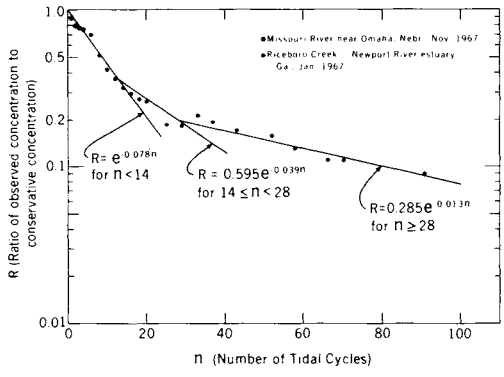

Fig. 5. Decay curve for Rhodamine WT dye (Time for the nontidal Missouri River is converted to equivalent n by assuming one tidal cycle = 12.4 hours).

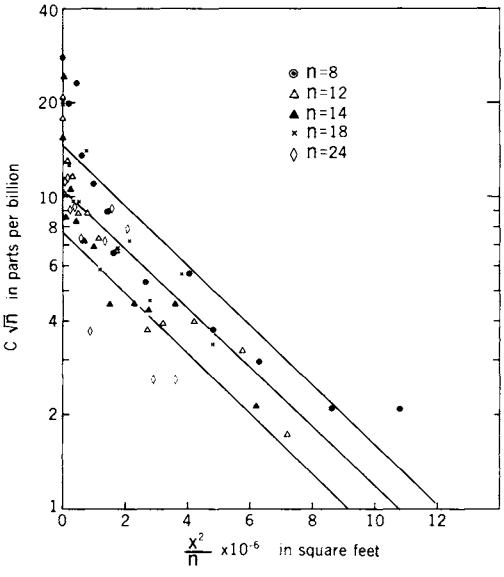

Fig. 6. Time variation of conservative solute concentration.

deviations from the curve, indicating that the value of K for the reach upstream from station 8 is smaller than the above value.

The average curve in Fig. 6 provided the following numerical values for equation 3,

$$\ln C\sqrt{n} = 2.359 - \frac{x^2}{45.711 \times 10^5 n} \quad (3')$$

where C is ppb, x in feet, and n designates the number of tidal cycles, and one tidal period, t_p, is assumed to be 12.4 hours. The extrapolation of dye concentration beyond the observation period was obtained by applying the appropriate decay rate of Fig. 5 to a conservative concentration which was calculated by means of equation 3′ at a specified number of tidal cycles and a specified station. The solid curve shown in Fig. 4 represents calculated dye concentration from equation 3′. The dotted line in Fig. 4, on the other hand, was estimated from early stage data.

When dye concentrations, in Fig. 4, are read off at two tidal cycle intervals and added together, the total is the buildup concentration which would result from the repeated injections of 5.7 pounds of Rhodamine WT per two tidal cycles. Table 1 shows the potential buildup concentration in ppb for an injection rate of 1 pound of Rhodamine WT per two tidal cycles at the headwater of the Muddy Creek.

Discussion and Conclusions

Because the dye test was conducted as a preliminary study under somewhat unfavorable tidal conditions, the results obtained from the test are tentative at best. If there is a demand for a more accurate investigation, another dye test should be conducted, in which a much larger amount of dye should be injected continuously over one or two tidal cycles. Timing of a new test should be such that the occurrence of irregular tides is avoided.

One interesting result of the present study was that peak dye concentration tended to move and stay upstream of the confluence in spite of the early sustained ebb tides, which moved peak concentrations downstream temporarily. Prior to the 8th tidal period, the upstream movement was mostly due to the rise of tidal stage which moved the whole dye cloud in the upstream direction. On the other hand, the movement at later periods indicates strongly the lack of significant freshwater inflow and shows the effect of the reflection of dye at the upstream end of the estuary because the dye was injected at the headwater area. (See Appendix). It is certain that built-up concentrations in the upstream area under low freshwater flow conditions will be much higher than those shown for downstream stations in Table 1.

TABLE 1. Ultimate builtup concentration resulting from the continuous injection at the rate of 1 pound of Rhodamine WT per two tidal cycles at the head of the tidal portion of Muddy Creek.

Station No.	Distance from the confluence in feet	Concentration in ppb
8	1,900	8
14	3,700	5
17	6,200	3
22	9,300	2

It is also certain that the average concentration of dye in water of the north fork will be as much as that of the south fork even if the release point is in the south fork of Muddy Creek, as major tidal water movement is through the north rather than the south fork.

The tracer study shows that at stations 8 through 22, steady state dye concentrations will occur at about 300 tidal cycles. For stations upstream from station 8, the buildup will be accomplished in a shorter number of tidal cycles.

In order to translate the test results for a tracer into information on actual waste concentration, it is important to realize that a tracer simulates the transport of similar solutes under prototype conditions. Thus the information should be used only for those waste materials that are soluble, and that mix with water in the same manner as the dye. A tracer normally does not simulate the decay characteristics of a particular waste. Thus, an additional calculation must be performed on tracer data, such as shown in Fig. 4. If an overall decay of such material is described also by an exponential relation similar to the dye, the following equation could be applied to dye concentration at a certain tidal cycle

$$C_{\text{waste}} = C_{\text{dye}} \frac{e^{-(P_w - B)n}}{\alpha}, \qquad (6)$$

where P_w is the decay constant of the waste material per tidal cycle, while the values of α and β are for Rhodamine WT as shown in Fig. 5. Since the overall decay rates of most waste materials coming from domestic sewages are higher than for Rhodamine WT, the corresponding concentration will be smaller for such waste materials than for the dye. The influence of decay constant on built-up time and concentration is so strong that an accurate evaluation of this parameter, P_w, is vital in evaluating the effects of actual waste releases. These data for wastes to be discharged into Muddy Creek are not available at the present time.

Conclusions

The water of the north fork will be contaminated as much as that of the south fork even if the effluent site is located in the south fork. An effluent site located near the headwater of Muddy Creek will cause high concentration buildup there when freshwater flow is small and dispersion is reflected at the upstream end of the estuary. Built-up concentrations due to continuous injection of Rhodamine WT at the headwater area will range from 8 ppb at 1,900 feet downstream from the confluence (station 8) to 2 ppb near the Smithsonian pier. Higher values are expected in the region upstream from station 8. The concentration is based on the release rate of one pound of dye per two tidal cycles. The tidal excursion of water particles starting at the headwater area is estimated to be about 3,200 feet. The longitudinal dispersion coefficient (see Appendix) in the Muddy Creek after 10 tidal cycles is 25.6 ft^2 per sec.

APPENDIX

Assume a tidal estuary with uniform cross-sectional geometry. For simplicity the variation of cross-sectional area with time and distance is neglected and the velocity is assumed to depend on time alone. The one-dimensional transport of a solute may then be described by

$$\frac{\partial C}{\partial t} + u(t)\frac{\partial C}{\partial x} = \frac{\partial}{\partial x}\left(\frac{k\partial C}{\partial x}\right), \qquad (7)$$

where C is solute concentration, u is the velocity, k is the longitudinal dispersion coefficient, x is distance, and t is time. If k is also assumed to depend on time only, two new variables may be introduced as

$$X = x - \int_0^t u\,dt, \qquad (8)$$

and

$$T = \frac{1}{K}\int_0^t k\,dt, \qquad (9)$$

where K is constant. Substituting X and T in

place of x and t, equation 7 is transformed to

$$\frac{\partial C}{\partial T} = K\frac{\partial^2 C}{\partial X^2}. \qquad (2)$$

For the case of estuary with cyclic tidal motion without any freshwater discharge, equation 2 could be applied to the time T which is n multiples of the tidal period t_p. Since $\int_0^{tp} u\,dt = 0$ and $\int_0^{ntp} k\,dt = nKt_p$, where K is a tidal average of k, X in equation 2 is the same as x and T represents nt_p.

With the above interpretation of equation 2, a solution is obtained for the case of an instantaneous release near the end of the estuary by use of the method of images (Glover, 1964). It is

$$C = \frac{M}{A\gamma\sqrt{4\pi KT}}\left[e^{-\frac{x^2}{4KT}} + e^{-\frac{(x+2h)^2}{4KT}}\right] \qquad (10)$$

where M is the total weight of solute released, A is the cross-sectional area, γ is the specific weight of water, and h is the distance between the injection site and the end of the estuary. The coordinate x is measured in the seaward direction and is 0 at the injection site. Equation 10 is reduced to eq. 1 of the text if h = 0.

Because of the reflection of solute at the upstream boundary, the location of peak concentration is not stationary at x = 0 as is the case for an unbounded estuary. Setting $\partial C/\partial x) = 0$ with C given by eq. 10 it is found that

$$\ln\left(-\frac{2h}{x} - 1\right) = \frac{h(h+x)}{KT} \qquad (11)$$

In addition to x = - h (upstream boundary), there is one more value of x that satisfies eq. 11. This value of x indicates the location of the peak and may be calculated numerically since no explicit equation for x is available from eq. 11. It is apparent, however, that such peak location is at x = 0 when T = 0, at - h< x <0 when T is finite, and at x = - h when T = ∞. In other words, the peak moves upstream from the site of injection as time increases.

The velocity of upstream movement of the peak is obtained by differentiating eq. 11 with respect to T. It is given by

$$\frac{dx}{dT} = \frac{K\left[\ln\left(-\frac{2h}{x} - 1\right)\right]^2}{\frac{2h^2\left(-\frac{h}{x} - 1\right)}{(2h+x)} - h\ln\left(-\frac{2h}{x} - 1\right)} \qquad (12)$$

Upstream velocity of the peak in the present study was estimated from equation 12 by assuming K = 30 ft^2/sec and h = 1,000 feet. It ranges from 0.04 ft per sec at an early stage (x = −0.1 h) to 0.3 ft. per sec at a later stage (x = −0.8 h). Even though these are hypothetical calculations at best, it shows that the velocity is quite substantial. It is noted, however, that in estuaries with large fresh water inflow, the inflow tends to move the peak downstream and will retard or even overcome the upstream movement due to the boundary reflection.

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