Development of a Tidal Prism Model and its Application to the Pagan River, Virginia

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DEVELOPMENT OF A TIDAL PRISM MODEL AND ITS APPLICATION
TO THE PAGAN RIVER, VIRGINIA

A THESIS
Presented to
The Faculty of the School of Marine Science
The College of William and Mary in Virginia

In Partial Fulfillment
Of the Requirements for the Degree of
Master of Arts

by

Angela D'Amico

1976
This thesis is submitted in partial fulfillment of the requirements for the degree of Master of Arts in Marine Science

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A simple, practical tidal prism model has been developed to calculate the equilibrium distribution of pollutants introduced into an estuarine system. The theory is adapted from Ketchum's modified tidal prism method for predicting flushing time in an estuary. The application of this method requires that there be complete mixing at high tide within each segment. Segmentation begins at the mouth, with each segment having a length equal to the local tidal excursion. That is, each segment is defined such that its low tide volume equals the total tidal prism minus the river flow landward from the inner boundary of the segment.

This model, which was applied to the Pagan River, a tributary of the James River, was derived from the principle of mass balance. The model was used to calculate high water salinity concentration throughout the estuary so that the predicted results could be compared with actual field data. Having verified the model in this way, other conservative pollutants can be used as input so that a high tide concentration of these substances can be calculated.
DEVELOPMENT OF A TIDAL PRISM MODEL AND ITS APPLICATION TO THE PAGAN RIVER, VIRGINIA
An estuary has been described as a semi-enclosed body of water which has free connection to the open sea and where there is a dilution of sea water by land drainage (Pritchard, 1959). The flow regime in estuaries is governed mainly by the interaction between freshwater runoff and the astronomical tide which causes a rise and a fall of the water surface. The rise and fall of the tide at the mouth causes an exchange of water masses through the entrance. This results in a temporary storage of large amounts of sea water in the estuary during flood tide and the drainage of this sea water during ebb tide. The total volume exchanged is known as the tidal prism. In estuaries, this volume varies only with tidal amplitude (Ippen, 1966).

Freshwater from upland sources entering the estuary during the flood tide reduces the amount of ocean water that would otherwise enter. A portion of the tidal prism is now filled with fresh water. The freshwater flow also increases the amount of water leaving the estuary during ebb tide. This reduction in inflow and increase in outflow results in a net flow in the ebb direction. The net result is that more water flows out of the estuary during ebb than flows in during flood. The escaping
volume is available for the dilution and removal of pollutants. Increased river flow causes both a downstream movement of the salinity intrusion and a more rapid circulation of water. Increased river discharge is accompanied by a more rapid exchange of fresh water with the sea. Thus, an increase in freshwater flow would increase the flushing in the estuary.

The basic non-tidal circulation associated with and active in maintaining the salinity distribution in estuaries, consists of a seaward flow of river water and a system of currents induced by the density difference between fresh water and sea water. In an estuary with high freshwater runoff with respect to the tidal prism, the flow profile is divided into two distinct layers (Farmer, 1952). The lower layer has practically the same salinity as the ocean. The upper layer is fresh with almost no influence from the sea. There is no net flow in the lower layer. The salt water moving upstream at the bottom is balanced by the flow moving seaward within the wedge. The interface forms the boundary through which practically no salt water moves to mix with the freshwater stream. Freshwater velocities in the upper layer increase seaward, reaching a maximum near the estuary entrance. The large density difference between fresh and sea water is capable of suppressing turbulent mixing and interfacial waves at the interface (Ippen, 1966).
In a partially mixed estuary, tidal currents produce noticeable vertical mixing of fresh and salt water. Gravitational convection results from the horizontal salinity gradient (Pritchard, 1969, Hansen and Rattray, 1965). Net velocities near the bottom are landward as a result of the different densities of fresh and saline waters. The net landward transport of saline waters in the deeper part of the channel must be compensated for in the upper portions of the depth by the seaward transport of these waters together with the net flux of freshwater downstream. A current system is produced, exhibiting a large scale gravitational circulation which is important for the flushing of fresh water and pollutants into the receiving salt water body.

When the ratio of freshwater runoff to the tidal prism becomes low, tidal action causes the estuary to become well mixed. Fresh and salt waters are fairly well mixed through the vertical direction and the flushing by gravitational circulation becomes less important.

An estuary may be changed from a highly stratified type to a partially or well mixed type by the reduction of the freshwater discharge. Conversely, by increasing freshwater flow, the change from well mixed to highly stratified may occur. In a well mixed estuary, tidal flushing is the dominant flushing mechanism. The water entering on the flood tide mixes with that inside. The
volume of sea water and river water introduced equals the tidal prism, the volume between high and low tide marks. Since the water brought into the estuary on flood tide is mixed with polluted estuarine waters, a portion of the pollutant brought in by the river would be flushed out of the estuary during each tidal cycle. If the mixing is complete at high tide, the flushing volume relates only to the ratio between the total tidal prism and the total volume of water in the estuary. This classical tidal prism theory was an early attempt to describe flushing in a tidal estuary. It is invalid primarily due to incomplete mixing throughout the entire estuary. Ketchum (1951) modified this tidal prism method by dividing the estuary into segments. In each segment, complete mixing is assumed at high tide. The length of each segment is defined by the tidal excursion or the average distance traveled by a particle of water on the flood tide, since this is the maximum length over which mixing can be assumed. The most landward segment is defined as the one above which the tidal prism ($P_o$) equals the river flow ($R$), during a tidal cycle.

A tidal creek or a bay presents conditions where there is a rise and fall of water due to tidal action. Here there may be no freshwater input due to river flow. There will be an excursion of a water particle during half a tidal cycle. The problem lies in determining
the initial segment since there will be no segment above which \( P_0 = R \).

Ketchum assumed that the water in each segment is completely mixed at high tide. The portion of water removed from each segment on the ebb is assumed not to return to that segment during the next flood tide. Verification of this situation is not presented in the original Ketchum model. It is possible that some of the water removed will return to its original segment due to tidal action. Assuming that the water in each segment is completely mixed at high tide, Ketchum argued that the portion of water removed on the ebb will be given by the ratio between the local intertidal volume and the high tide volume of each segment. This exchange ratio, \( r_n \), or flushing rate is expressed mathematically as

\[
    r_n = \frac{P_n}{P_n + V_n}
\]

where \( P_n \) is the local intertidal volume and \( V_n \) is the local low tide volume of the nth segment. This calculation of the flushing rate is acceptable in a small coastal basin, which can be considered as a single segment. In this case, the prism volume from the sea mixes completely with the low tide volume of the estuary. A volume of mixed water escapes during the ebb tide and is assumed not to return. Ketchum's argument that this
flushing rate can be calculated for each segment of a multi-segmented estuary is not valid. To assume that the local tidal prism of each segment contains only water introduced by the flood tide from the open sea is incorrect. This prism volume contains some water that was present in the tidal prism upstream of that segment, as well as some water that was contained in the low tide volume of the seaward segments. At ebb tide, a segment has a net decrease in volume equivalent to the local tidal prism, but it receives water from the landward segment while flushing water to the seaward segment. The segments, therefore, cannot be handled as separate units, each with its flushing rate dependent on the local tidal prism and the segment volume. Although the interaction between the segments of an estuary was neglected in the original Ketchum formulation, the estuary is a complete system that cannot be broken down into isolated units.

The purpose of this research is to refine Ketchum's development by incorporating some of his basic ideas in a tidal prism model. Some of the inconsistencies of the original model have been resolved. Segmentation in the presented model begins at the mouth, thus solving the problem of defining the initial segment in case the freshwater runoff is zero. The segment length is still defined as the tidal excursion. The mass balance
relationship is derived with a more rigorous approach. This type model is convenient to use as it only requires a minimum amount of data: the tidal range, freshwater flow and basin topography. In small coastal basins, application of advanced numerical mathematical modeling techniques requires a large investment of time. This model's effectiveness lies in its simplicity. Average high tide concentrations of a conservative pollutant are predicted for each segment.

Segmented tidal prism models predict mixing phenomena from the physical characteristics of the estuary alone. Salt water intrusion into an estuary is a direct result of the mixing process. Since the only source of salt is ocean water and because salt is a conservative substance, an analysis of salinity distribution is adequate to describe the mixing process (DiToro, 1969). The model presented was used to calculate high water salinity concentration throughout the estuary so that predicted results could be compared with actual field data. Having verified the model in this way, other conservative pollutants can be used as input so that a high tide concentration of these substances can be calculated. A description of the mathematical formulation is presented in Chapter II. Chapter III presents the results of the applications of the model on the Pagan River, Virginia.
II. MATHEMATICAL FORMULATION

A. Basic Assumptions

Some of Ketchum's assumptions of the tidal prism concept are retained in this model. The inter-tidal volume of water serves to dilute the introduced pollutants and eventually flushes them out of the estuary. It is assumed that the estuary or coastal creek is in hydrodynamic equilibrium. That is, the river flow is constant and the net seaward transport of fresh water over a tidal cycle equals the volume of river water introduced during the same period. There is no net exchange of salt during a tidal cycle. This implies a balance between the inflow and outflow of sea water. A constant pollutant discharge rate is also assumed.

B. Segmentation of Estuaries

With the segment length equal to the tidal excursion, an estuary is segmented beginning at the mouth. The water body outside of the mouth is assumed to be the first segment. The first segment within the estuary is indexed as the second one, bound by transects one and two. The first transect is across the mouth, the second transect is chosen such that a water particle will move from the first to the second over flood tide. Therefore,
\[ V_2 = P_2 - R_2 \]

where \( V_2 \) is the low tide volume of the second segment, \( P_2 \) is the tidal prism upstream of the second transect and \( R_2 \) is the river flow upstream of the second transect.

In general, a water particle at the nth transect should move to the \((n + 1)\)th transect at the end of the flood tide. By this assumption

\[ V_n = P_n - R_n \quad (1) \]

(as shown in figure 1)

or \[ V_n = P_{n+1} - R_{n+1} - P_{n+1} - r_{n+1} \quad (2) \]

or \[ V_n = V_{n+1} + P_{n+1} - r_{n+1} \quad (3) \]

where

\[ V_n = \text{low tide volume of the nth segment} \]
\[ P_n = \text{tidal prism upstream of the nth transect} \]
\[ R_n = \text{total freshwater discharge through the nth transect over half a tidal cycle} \]
\[ P_n = \text{local tidal prism of the nth segment} \]
\[ r_n = \text{freshwater input into the nth segment over half a tidal cycle} \]

From equation (1), it is seen that \( V_n \) tends to zero as \( P_n \) tends to zero near the head of the estuary. Therefore, there is an infinite number of segments. This is in agreement with the fact that the tidal excursion tends toward zero at the head of the estuary. Mixing is
Figure 1. Schematic representation of the criteria for segmentation.
never completed at this landward end since the tidal excursion is greatly reduced.

Segmentation is continued until \( P_{n+1} \geq 3R_{n+1} \). This condition is described in section D of this chapter (see equation 4). Therefore, for all segments, \( P_{n+1} \geq 3R_{n+1} \). Once this constraint does not hold, the remainder of the estuary is combined into one single segment, the Nth segment, as shown in figure 1. The prism upstream of the Nth transect equals the upstream freshwater discharge, that is \( P(N) = R(N) \). If there is no river flow, this method of segmentation is still valid. In this case, segmentation can be continued as long as one wishes. The last one includes the remainder of the tidal creek or estuary.

The length of the Nth segment so determined is larger than the local tidal excursion and complete mixing cannot be achieved within this segment. However, the concentration of this segment predicted by the model still represents the average of the segment.

C. Determination of Segment Lengths

Figure 2 shows for a hypothetical estuary its accumulated low tide volume, \( V(x) \), and the difference between the tidal prism and the river flow upstream of a point, \( (P(x) - R(x)) \), plotted as a function of \( x \), the distance from the mouth. \( V(x) \) is defined as the accumulated low tide volume from the mouth to some
Figure 2. Graphical determination of segment lengths for an estuary without tributaries.
transect located a distance x from the mouth. P(x) is defined as the inter-tidal volume upstream of a transect located at x. R(x) is defined as the freshwater input, also upstream of a transect located at x. The values for V(x) and (P(x) - R(x)) can be tabulated and graphed as shown in figure 2.

Since the segment length equals the tidal excursion, the low tide volume of the first segment within the estuary should equal the inter-tidal volume minus the river flow over a half tidal cycle upstream of the segment's landward boundary. This point, where V(2) = (P(2) - R(2)) can be determined graphically. The volume P(1) represents the entire intertidal volume of the estuary. Similarly, the volume R(1) represents the entire freshwater input into the estuary, including lateral inflow. These values are not used directly in the calculation, since the first low tide volume considered is V(2). V(1) is meaningless, as it is located outside the mouth. The initial segment, therefore is indexed as segment two. Once the initial segment is determined, successive segments are determined graphically, as shown in figure 2. Segmentation continues until the boundary constraint previously mentioned is violated.

For an estuary with tributaries, P(x) is similarly defined, only now it includes the intertidal volume of the tributaries. R(x) is defined such that the freshwater
input from the tributaries is included. The value $V(x)$ remains as the low tide volume along the main stem. These volumes are shown graphically in figure 3. Once again, the initial segment is determined such that the low tide volume $V(2)$ equals the intertidal volume minus the river flow upstream of that point. In a segment where a tributary comes in, the local low tide volume equals the tidal prism landward of it plus the prism minus the river flow of the branch. Each of the tributaries may be segmented in the same way as that of the main stem.

D. Calculation of Pollutant Concentrations

As the tide propagates upstream from the mouth, the volume of water $(P_{n-1} - R_{n-1})$ moves upstream across the $(n-1)$th transect and mixes with the water $V_n$ present in the $n$th segment at low tide. Of this mixed water, the portion $(P_n - R_n)$ moves upstream across the $n$th transect and is mixed completely with $V_{n+1}$ and so forth. At the ebbing tide, the volume of water $(P_n + R_n)$ moves downstream across the $n$th transect, pushing a volume $(P_{n-1} + R_{n-1})$ across the $(n-1)$th transect, and so forth, thus completing tidal flushing.

The flow across the transects bounding the $n$th segment is shown in figure 4.
Figure 3. Graphical determination of segment lengths for an estuary with tributaries.
At ebb tide, the water volume moving across the nth transect, \((P_n + R_n)\), may be separated into two parts, except for the last transect of the estuary. The first part is the water in the \((n+1)\)th segment at high tide. This is

\[
V_{n+1} + P_{n+1} = P_{n+1} - R_{n+1} + P_{n+1} \\
= P_n - R_{n+1}
\]

This volume has concentration \(C_{1n+1}\) where \(C_{1n+1}\) equals the high tide concentration in the \((n+1)\)th segment during the present tidal cycle. The remainder of the
water can be represented as

\[(P_n + R_n) - (V_{n+1} + P_{n+1})\]

\[= P_n + R_n - (P_n - R_{n+1})\]

\[= R_n + R_{n+1}\]

This volume, \(R_n + R_{n+1}\), has the concentration \(C_{1n+2}\) assuming

\[R_n + R_{n+1} < V_{n+2} + P_{n+2}\]

\[= P_{n+2} - R_{n+2} + P_{n+2}\]

\[= P_{n+1} - R_{n+2}\] (4)

or

\[P_{n+1} > R_n + R_{n+1} + R_{n+2}\]

\[P_{n+1} > 3R_{n+1}\]

The segmentation should be stopped before the inequality is violated. If violated, the volume of water \(R_n + R_{n+1}\) will have a concentration that depends on \(C_{1n+3}\) as well as \(C_{1n+2}\). The mass transport into and out of the nth segment during ebb tide may be expressed as

\[\text{mass in} = ETP_n = \text{Ebb Tide Transport into the nth segment}\]

\[(P_n - R_{n+1}) C_{1n+1} + (R_n + R_{n+1}) C_{1n+2}\]

\[+ r_n B C_n\]
The last term is added to include the lateral inflow into this segment during the half tidal cycle. This volume has concentration $BC_n$.

\[
\text{mass out} = ETP_{n-1} = \text{Ebb Tide Transport out} \quad \text{out the nth segment}
\]

\[
(P_{n-1} - R_n) C_{1n} + (R_{n-1} + R_n) C_{1n+1}
\]

The last, Nth segment has a volume larger than that set by the criteria of segmentation. Therefore, the volume of water moving through the Nth segment must be considered separately. The volume moving into the Nth segment equals $2R_N$ or the river flow over a tidal cycle. This volume has concentration $C_{1N+1}$. The volume leaving the segment equals $P_{N-1} + R_{N-1}$ which would have concentration $C_{1N}$ only. The mass transport into and out of the Nth segment during ebb tide may be expressed as

\[
\text{mass in} = ETP_N = \text{Ebb Tide Transport into the Nth segment}
\]

\[
2R_N C_{1N+1} + r_N BC_N
\]

The last term is added to include the lateral inflow into this segment during the half tidal cycle. This volume has concentration $BC_N$.

\[
\text{mass out} = ETP_{N-1} = \text{Ebb Tide Transport out of the Nth segment}
\]

\[
(P_{N-1} + R_{N-1}) C_{1N}
\]
These values are calculated separately in the computer program.

Some of the water that leaves the nth segment during ebb tide might return during the following flood tide. Ketchum did not account for this fact in the original model. A returning ratio, \( \alpha_n \) is defined such that \( 100\alpha_n \% \) is the percentage of old water reentering through the nth segment at flood tide. The fraction of new water entering through the nth transect at flood tide may be expressed as \( (1-\alpha_n) \).

At flood tide, the volume \( (P_n - R_n) \) flowing through the nth transect has the concentration

\[
\alpha_n C_{n+1} + (1-\alpha_n) C_{2n}
\]

where \( C_{2n} \) equals the high tide concentration at the next tidal cycle. The mass transport into and out of the nth segment during flood tide may be expressed as

\[
\text{mass in} = FTP_{n-1} = \text{Flood Tide Transport into the nth segment}
\]

\[
\{\alpha_{n-1} C_n + (1-\alpha_{n-1}) C_{2n-1}\} (P_{n-1} - R_{n-1}) + r_n B C_n
\]

Again, this last term is added to include the lateral inflow into this segment during the half tidal cycle.

\[
\text{mass out} = FTP_n = \text{Flood Tide Transport out of the nth segment}
\]

\[
\{\alpha_n C_{n+1} + (1-\alpha_n) C_{2n}\} (P_n - R_n)
\]
The change of mass, $\Delta m$, with respect to time is

$$\frac{\Delta m}{\Delta t} = \text{source} + (\text{mass in}) - (\text{mass out})$$

In the present development, the change of mass over the entire tidal cycle can be represented as

$$\begin{align*}
(C2_n - C1_n) (V_n + p_n) &= \text{sources} + ETP_n - ETP_{n-1} + FTP_{n-1} - FTP_n \\
\text{or} \quad (C2_n - C1_n) (V_n + p_n) &= \text{sources} + ETP_n - ETP_{n-1} \\
& \quad + \{\alpha_{n-1} C1_n + (1 - \alpha_{n-1}) C2_{n-1}\} (P_{n-1} - R_{n-1}) \\
& \quad - \{\alpha_n C1_{n+1} + (1 - \alpha_n) C2_n\} (P_n - R_n)
\end{align*}$$

(5)

(6)

Letting $VH_n = V_n + p_n$ and $PRF_n = P_n - R_n$, the equation can then be solved for $C2_n$.

$$C2_n = \{C1_n + \frac{\text{sources}}{VH_n} + \frac{ETP_n - ETP_{n-1}}{VH_n}
\frac{PRF_{n-1}}{VH_n} \{\alpha_{n-1} C1_n + (1 - \alpha_{n-1}) C2_{n-1}\}
- \frac{PRF_n}{VH_n} \{\alpha_n C1_{n+1} + \frac{r_n BC_n}{VH_n}\}
\{1 + \frac{PRF_n}{VH_n} (1 - \alpha_n)\}$$

(7)

If $N$ is the total number of segments, $(N-1)$ equations will be obtained by writing equation (7) for $n=2$ to $N$. The $(N-1)$ equations may be solved for the $(N-1)$ unknowns, $C2_n$, if the initial concentrations,
and two boundary conditions, \( C_{21} \) and \( C_{1N+1} \) are specified. The principal operation of the numerical computation is then to compute the concentrations in each segment at the first tidal cycle with a given or assumed initial concentration field at the zeroth tidal cycle. The computed concentration field at the first tidal cycle will then be used as the initial condition to compute the concentration field at the second tidal cycle, and so forth. Each computation cycle will advance time by the increment of one tidal cycle until a specified tidal cycle or equilibrium concentration field is reached. Within each computation cycle, the \((N-1)\) equations are solved by successive substitution, since \( C_{2n-1} \) is the only unknown upon which \( C_{2n} \) depends.
III. CASE STUDY

A. Summary of the Present Study

Two sets of calculations presented in this chapter are made to illustrate the potential of the model to produce estuarine behavior. The first study simulates the salinity distribution of the Pagan River with a freshwater discharge of 6 cfs at the head of the estuary. The determination of the value of the returning ratio, $\alpha$, was made by a sensitivity analysis run under this condition. Application of the original Ketchum model was made under this same condition to illustrate its shortcomings. The results obtained from both models are compared to actual field data. The second calculation study offers verification of the model and of the previously determined value of $\alpha$. The freshwater discharge in this case was reduced to 3 cfs. The results obtained are compared to existing field data.

B. Hydrography of the Pagan River

The Pagan River is a small tributary on the south bank of the James River. The drainage basin is small (67 square miles or 174 square kilometers). In the spring, 1974, eleven bathymetric profiles were taken to acquire geometric data. Three more bottom profiles were
Figure 5. Location of the bathymetric cross sections (statute miles).
added in the spring of 1975 (Kuo, et al., 1976). Their locations are shown in figure 5. From these profiles, low tide and inter-tidal cross sectional areas were calculated for each transect. The corresponding low tide volume and tidal prism for each segment enclosed by adjacent transects were calculated.

Freshwater runoff is usually small for the Pagan River (under 10 cfs) (Kuo, et al., 1976). The model was run for two cases; in July, 1975 with upstream freshwater discharge of 6 cfs and in August, 1974 with upstream freshwater discharge of 3 cfs. The lateral freshwater input into each segment was calculated as a function of drainage area using the corresponding freshwater discharge and drainage area at the head.

In this study, salt is the substance being considered. Therefore, the boundary condition $C_2(l)$ is the only forcing function of the concentration field. This value equals the average salinity at the mouth at the time of the study, which data was obtained from field data collected by the Virginia Institute of Marine Science on intensive surveys carried out in July, 1975 and August, 1974. Since the first segment is outside the mouth, the value of $C_2(l)$ is kept constant for each tidal cycle. The concentration, $C_{1,N+1}$, in the $(N+1)$th segment is set equal to zero. This is in agreement with the fact that $R(N) = P(N)$ and the water above the $N$th segment consists of fresh water only. The value of the
river flow upstream of the Nth segment, \( R(N) \), is the upstream freshwater discharge over a half tidal cycle.

The values of \( C_2 \) from 2 to \( N \) are then calculated for the first tidal cycle. The values of \( C_1 \) are reinitialized for each segment, such that \( C_1(n) \) equals \( C_2(n) \) for the previous tidal cycle calculated. This process is continued for the number of tidal cycles specified in the input data. In each case, the predicted salinity is compared to the observed salinity, averaged over depth, recorded on these surveys. The salinity calculated by the model represents the average salinity of each segment.

C. Determination of Segment Lengths

The criteria for segmentation presented in Chapter II were followed in segmenting the Pagan River. In each segment, the constraint that \( P_{n+1} \geq 3R_{n+1} \) was upheld. Once this boundary condition was violated, the rest of the estuary was combined into one large segment, forming the last, Nth segment. Though the salinity calculated in this last segment was the average salinity of the segment, in reality, it is expected that the salinity variation will be large within the segment since the segment length is much larger than the tidal excursion. The prism upstream of this segment, \( P(N) \), equals the river flow, \( R(N) \), during half a tidal cycle. The segmentation and corresponding volumes are shown for both conditions which were run. Table 1 shows the data for July,
1975 and table 2 shows the data for August, 1974. Figures 6 and 7 show the location of the segments for July, 1975 and August, 1974 respectively.

D. Determination of the Returning Ratio

The returning ratio, $\alpha$, can take on a value between 0 and 1, inclusively. If $\alpha$ equals 0, no old water would return into the segment during the next tide. If $\alpha$ equaled 1, all the water flushed out of the segment by the ebb tide would return during the following flood tide. To determine the value of $\alpha$ for the present study, a sensitivity analysis was run for the July, 1975 conditions. The value of $\alpha$ was set equal to 0, and then incremented by .1 until the maximum value of 1 was reached. By comparing the predicted salinities with the actual field data, the optimum value of $\alpha$ was found to lie between .3 and .4. The average value of $\alpha = 0.35$ was determined as the best value to be used in this study. The results of the sensitivity analysis are shown in figure 8. Figure 9 shows the results of the model run for the condition of July, 1975 with $\alpha = 0.35$. This value of $\alpha$ was used when the model was run with the condition of August, 1974. In both cases, the model was run for 100 tidal cycles. The predicted salinities in this case showed good agreement with actual field data, as shown in figure 10. This serves to verify the model and the value of $\alpha$ chosen from the previous set of conditions.


<table>
<thead>
<tr>
<th>Segment(n)</th>
<th>Length (sm)</th>
<th>Low Tide Volume (x10^6 ft^3)</th>
<th>Accumulated P(x) - R(x) (x10^6 ft^3/half tide)</th>
<th>P(x) (x10^6 ft^3/half tide)</th>
<th>RLOCAL (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>--</td>
<td>--</td>
<td>72.9</td>
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<td>.1348</td>
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<tr>
<td>Segment(n)</td>
<td>Length (sm)</td>
<td>Accumulated Low Tide Volume (x10^6 ft^3)</td>
<td>R(x)</td>
<td>P(x) (x10^6 ft^3/half tide)</td>
<td></td>
</tr>
<tr>
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<td>--</td>
<td>--</td>
<td>--</td>
<td></td>
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<td>45.92</td>
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<tr>
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<td>7.4</td>
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<td>7.4</td>
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<td>2.01</td>
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<td>.16</td>
<td>.39</td>
<td>.39</td>
<td>.83</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Figure 6. Location of the transects bounding the segments determined for 6 cfs (statute miles).
Figure 7. Location of the transects bounding the segments determined for 3 cfs (statute miles).
Figure 8. Determination of the value of $\alpha$ by a sensitivity analysis.
Figure 9. Predicted salinities compared to actual field data for the July, 1975 conditions.
Figure 10. Predicted salinities compared to actual field data for the August, 1974 conditions.
PAGAN RIVER  AUGUST 1974

\[ \alpha = 0.35 \]

- Observed Salinity
- Predicted Salinity

HIGH WATER SLACK SALINITY (‰)

DISTANCE FROM MOUTH (STATUTE MILES)
E. Determination of the Time Required to Reach Equilibrium

The model was run for 100 tidal cycles. This time period was proved sufficient by examining the predicted salinities as a function of time for two arbitrarily picked segments. The salinities of segments 2 and 9 are observed and graphed. The conditions run were for upstream freshwater discharge of 6 cfs and the returning ratio, $\alpha = 0.35$. Figures 11 and 12 show that these predicted salinities increase regularly and then remain essentially constant, indicating that the steady state condition has been reached. The times required for the salinity to reach 95% of equilibrium value were 30 and 50 tidal cycles for segments 2 and 9 respectively.

F. Application of the Ketchum Model to the Pagan River

The Pagan River was segmented from the head, according to Ketchum's criteria, for the July, 1975 condition. The first segment is the one in which $P_o = R$, where $R$ is equivalent to 6 cfs. The rest of the river is segmented such that the low tide volume equals the high tide volume of the adjacent landward segment. The surface area of the Pagan River increases regularly from the head, until 2 miles downstream, where it decreases and then increases regularly again. This causes the local tidal prism to decrease in that area. The exchange ratio, $r_n$, is dependent on the local prism volume. If
Figure 11. Determination of the equilibrium concentration for segment 2.
Figure 12. Determination of the equilibrium concentration for segment 9.
the local prism volume suddenly decreases it affects
the exchange ratio by causing it to become quite low,
as shown in table 3. The variation in the exchange
ratio causes a corresponding variation in the predicted
salinities. The salinity distribution predicted does
not show a gradual increase of salinity from the head
to the mouth of the estuary.

Using Ketchum's formulation, an expression for
the salinity in parts per thousand has been developed.
The freshwater fraction, \( F_n \), is defined as the fraction
of freshwater present in the \( nth \) segment. Expressed
mathematically, \( F_n = \frac{S_o - S_n}{S_o} \), where \( S_o \) is the salinity
outside the mouth and \( S_n \) is the salinity in the \( nth \)
segment. If \( Q_n \) is the total volume of fresh water
accumulated in the \( nth \) segment, according to Ketchum's
formulation, \( Q_n = \frac{R}{r_n} \) (Ketchum, 1951), where \( R \) is now
defined as the river flow over a tidal cycle. Letting
\( \Psi_n \) = the high tide volume of the \( nth \) segment, the fresh-
water fraction may also be represented as

\[
F = \frac{Q_n}{\Psi_n} = \frac{S_o - S_n}{S_o}
\]

Solving for \( S_n \)

\[
S_n = (1 - \frac{Q_n}{\Psi_n}) S_o
\]
TABLE 3
SEGMENTATION OF PAGAN RIVER USING
ORIGINAL KETCHUM CRITERIA (RIVER FLOW = 6 cfs)
(Segmentation begins at the Head of the Estuary)

<table>
<thead>
<tr>
<th>Segment</th>
<th>Length (sm)</th>
<th>LOCAL VOLUMES</th>
<th>Exchange Ratio ($r_n$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Intertidal ($P_n$)</td>
<td>High Tide ($P_n+V_n$)</td>
</tr>
<tr>
<td>0</td>
<td>0.12</td>
<td>0.27</td>
<td>0.63</td>
</tr>
<tr>
<td>1</td>
<td>0.22</td>
<td>0.28</td>
<td>0.91</td>
</tr>
<tr>
<td>2</td>
<td>0.24</td>
<td>0.71</td>
<td>1.62</td>
</tr>
<tr>
<td>3</td>
<td>0.26</td>
<td>0.99</td>
<td>2.61</td>
</tr>
<tr>
<td>4</td>
<td>0.76</td>
<td>1.43</td>
<td>4.04</td>
</tr>
<tr>
<td>5</td>
<td>0.45</td>
<td>0.92</td>
<td>4.96</td>
</tr>
<tr>
<td>6</td>
<td>0.52</td>
<td>0.95</td>
<td>5.91</td>
</tr>
<tr>
<td>7</td>
<td>0.53</td>
<td>1.08</td>
<td>6.99</td>
</tr>
<tr>
<td>8</td>
<td>0.51</td>
<td>2.07</td>
<td>9.06</td>
</tr>
<tr>
<td>9</td>
<td>0.49</td>
<td>3.52</td>
<td>12.58</td>
</tr>
<tr>
<td>10</td>
<td>0.63</td>
<td>4.51</td>
<td>17.09</td>
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<tr>
<td>11</td>
<td>0.93</td>
<td>10.27</td>
<td>27.36</td>
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<tr>
<td>12</td>
<td>0.88</td>
<td>12.6</td>
<td>39.96</td>
</tr>
<tr>
<td>13</td>
<td>1.15</td>
<td>18.7</td>
<td>58.66</td>
</tr>
</tbody>
</table>
Letting \( Q_n = \frac{R}{r_n} \) and \( r_n = \frac{P_n}{v_n} \)

\[
S_n = (1 - \frac{R}{P_n}) S_0
\]

Within the first statute mile, the salinities range from 0 to over 8 parts per thousand. This is not in agreement with actual salinity distribution found in the Pagan River. Salinities obtained using the exchange ratio of the Ketchum model are compared to the salinities predicted by the proposed model as well as to actual field data in figure 13.
Figure 13. Salinities predicted by the original Ketchum model and the proposed model compared to actual field data for the July, 1975 conditions.
COMPARISON OF MODEL RESULTS
PAGAN RIVER
JULY 1975

DISTANCE FROM MOUTH (STATUTE MILES)

HIGH WATER SLACK SALINITY (%o)

Observed Salinity by Proposed Model
Predicted Salinity by Ketchum Model
IV. CONCLUSIONS AND RECOMMENDATIONS

The proposed tidal prism model gives a good representation of the salinity distribution in the Pagan estuarine system. The mixing process in the system can be examined by following the distribution of salt, a natural tracer of water movements. This model is a significant improvement to the original Ketchum tidal prism model. Ketchum's development was an early attempt to describe the mixing process in estuaries. The inconsistencies found in the original model have been resolved. Segmentation begins at the mouth, solving the problem of defining the initial segment if there is no freshwater runoff. The problem of the local tidal prism of each segment containing only water introduced by the flood tide has been solved. A returning ratio, \( \alpha_n \), has been defined to describe the fraction of old water reentering through the nth segment at flood tide. The sensitivity analysis run on the Pagan River has determined the value of \( \alpha_n \) to be 0.35. This value offers good agreement with the actual field data on both cases run. For future application of the model, it is suggested that a similar analysis be run on the system to be studied. The value of \( \alpha \) can be verified by comparing the results obtained from the sensitivity analysis to actual field data.
Once verified, a can be used in the determination of other conservative pollutant concentrations.

The model is not valid in a large estuarine system where the tide travels as a progressive wave. The formulation of mass-balance relationship in Chapter II requires that high water must occur at the same time throughout the estuary. The assumption that tidal mixing is dominant restricts the use of model to more or less well-mixed estuaries and tidal creeks.

The model should be applied to other small estuarine systems to verify its effectiveness. Further research may expand the model to incorporate non-conservative pollutants. An expression has been developed to predict the concentration of a conservative pollutant for each tidal cycle. This expression may be expanded to incorporate decay rates associated with non-conservative pollutants.

Estuaries are susceptible to pollution. Mathematical models offer a tool to examine the results of proposed changes in pollutant discharge in a small coastal basin. A simple, practical tidal flushing model has been presented that requires a minimum amount of input data and computer time. It takes less than 15 seconds to simulate 100 tidal cycles on the IBM 370. The model is sufficient for the steady state condition. The tidal prism concept has been shown to effectively simulate the salinity distribution.
APPENDIX A

The Computer Program
MODULE BASED ON TIDAL PRISM CONCEPT
COMMON/PHYSIC/V(100),VH(100),P(100),PLOCAL(100),RLOCAL(100),AL(100),CAL(100),R(100),ETP(100),FTP(100),PRF(100),PRE(100)
COMMON/QUAL/QWAST(100),WBOD(100)
COMMON/CON/C1(100),C2(100)
DIMENSION NTOUT(50)
IR=5
IW=6
C N IS THE NUMBER OF SEGMENTS
READ(IR,1) N
1 FORMAT(15)
WRITE(IW,2) N
2 FORMAT(1X,'TOTAL NUMBER OF SEGMENTS=',I5)
READ(IR,3) NTMAX, NTN
3 FORMAT(15)
READ(IR,4)(NTOUT(I),I=1,NTN)
4 FORMAT(10I5)
CALL PHYDA(N)
CALL INPUT(N,DISCH)
R(N)=DISCH
N1=N-1
DO 100 K=1,N1
I=N-K
R(I)=R(I)+RLOCAL(I+1)
100 CONTINUE
DO 110 K=1,N1
PRE(K)=P(K)-R(K+1)
PRF(K)=P(K)-R(K)
110 CONTINUE
PRF(N)=0.
C UPSTREAM BOUNDARY CONDITION
C1(N+1)=WBOD(N+1)/24.0*6.21/DISCH/62.4
C2(1)=C1(1)
NT=0
KW=1
N2=N-2
200 NT=NT+1
DO 205 K=1,N2
ETP(K)=(VH(K+1))*C1(K+1)+(R(K)+R(K+1))*C1(K+2)
205 CONTINUE
DO 206 K=1,N1
FTP(K)=(P(K)-R(K))*(AL(K)*C1(K+1)+CAL(K)*C1(K))
206 CONTINUE
ETP(N1)=(P(N1)-R(N1))*C1(N)
FTP(N)=2.0*R(N)*C1(N+1)
FTP(N)=0.0
DO 210 K=2,N
C2(K)=(C1(K)+WBOD(K)+(ETP(K)-ETP(K-1))/VH(K)+PRF(K-1)/VH(K)*AL(K-1))*C1(K)+CAL(K-1)*C2(K-1)-PRF(K)/VH(K)*AL(K)*C1(K+1))/(1.0+PRF(K))/2/VH(K)*CAL(K))
210 CONTINUE
IF(NT.EQ.NTOUT(KW)) GO TO 250
GO TO 260
250 WRITE(IW,31) NTUUT(KW)
31 FORMAT(1H1,6(' '),*CONCENTRATION AT ',I4,2X,'TIDAL CYCLES AFTER
1COMPUTATION BEGIN',6(' '),/)
   WRITE(IW,33) (K,C2(K),K=1,N)
33 FORMAT(5(I5,5X,F10.3))
   IF(NT.GE.NTMAX) GO TO 600
   KW=KW+1
260 DO 270 K=2,N
   C1(K)=C2(K)
270 CONTINUE
GO TO 200
600 CALL EXIT
END

SUBROUTINE PHYDA(N)
COMMON/PHYSIC/V(100),VH(100),P(100),PLOCAL(100),RLOCAL(100),AL(100),CAL(100),K(100),ETP(100),FTP(100),PRF(100),PRE(100)
DIMENSION TITLE(35),NAME(30)
IR=5
IW=6
READ(IR,2) TITLE
2 FORMAT(1X,35A2)
WRITE(IW,4)
4 FORMAT(1H1)
WRITE(IW,2) TITLE
C READ AND COMPUTE
100 READ(IR,6) NDG,NS,NAME
6 FORMAT(2I5,30A2)
   IF(NDG-99) 200,300,300
200 WRITE(IW,10) NDG,NS,NAME
   FORMAT(/1X,'INPUT DATA GROUP=',I4,4X,'NUMBER OF POINT IN THIS GRO
1UP=',I4,4X,30A2/)
   GO TO (11,21,31,41,31),NDG
11 CONTINUE
20 FORMAT(7F10.0)
   READ(IR,20)(V(I),I=1,NS)
   READ(IR,20)(P(I),I=1,NS)
   DO 25 K=2,NS
      PLOCAL(K)=P(K-1)-P(K)
   VH(K)=V(K)+PLOCAL(K)
25 CONTINUE
   GO TO 100
21 READ(IR,20)(RLOCAL(I),I=1,NS)
   C CHANGE RLOCAL FROM CFS TO 10**6 CUBIC FEET PER HALF TIDE
   GO TO 100
31 READ(IR,20)(AL(I),I=1,NS)
   DO 35 K=1,NS
      CAL(K)=1.0-AL(K)
35 CONTINUE
   GO TO 100
300 CONTINUE
WRITE(IW,55)
SUBROUTINE INPUT(N,DISCH)

COMMON/PHYSIC/V(100),VH(100),P(100),PLGCAL(100),RLOCAL(100),AL(100),CAL(100),R(100),ETP(100),FTP(100),PRF(100),PRE(100)

COMMON/QUAL/QWAST(100),WBOD(100)

COMMON/CON/C1(100),C2(100)

DIMENSION TITLE(35),NAME(30)

IR=5
IW=6
WRITE(IW,2)

FORMAT(1H1)
READ(IR,4) TITLE
WRITE(IW,4) TITLE

READ(IR,6) NDG,NS,NAM£
FORMAT(2I5,30A2)
IF(NDG-99) 55,200,2 00
WRITE(IW,910)NDG,NS,NAME
10 FORMAT(/1X,'INPUT DATA GROUP=',4X,'NUMBER OF POINT IN THIS GROUP=',4X,5G2//)
GO TO !10i,111,121,131,141,151,161,171),NDG

12 FORMAT(7F10.0)
CONTINUE
READ(IR,12) (Cl(I),I=1,NS)

WRITE(IW,19)
19 FORMAT(/1X,'********** INITIAL CONCENTRATIONS **********')
WRITE(IW,14) (1,C1(I),I=1,NS)

14 FORMAT(/1X,15,F10.2)
GO TO 40

C WASTE LOADS INPUT
121 CONTINUE
WRITE(IW,15)

15 FORMAT(1X,'REACH NO.',3X,'WASTE FLOW IN CFS',5X,'CBOD')
DO 125 I=1,NS
READ(IR,16)K,QWAST(K),WBOD(K)
16 FORMAT(15,5X,2F10.0)
WRITE(IW,17)K,QWAST(K),WBOD(K)
17 FORMAT(1X,15,7X,F10.0,8X,F10.0)
IF(K.GT.N) GO TO 125
WBOD(K)=WBOD(K)/24.0*12.42/62.4/VH(K)
125 CONTINUE
GO TO 40
131 CONTINUE
141 CONTINUE
151 CONTINUE
161 CONTINUE
171 CONTINUE
200 CONTINUE
RETURN
END

BLOCK DATA
COMMON/PHYSIC/V(100),VH(100),P(100),PLOCAL(100),RLOCAL(100),AL(1100),CAL(100),R(100),ETP(100),FTP(100),PRF(100),PRE(100)
COMMON/QUAL/QWAST(100),WBOD(100)
COMMON/CON/C1(100),C2(100)
DATA V,VH,RLOCAL,K,AL/500*0.0/ DATA CAL/100*1.0/
DATA QWAST,WBOD/200*0.0/ DATA C1,C2/200*0.0/
END
APPENDIX B
PROGRAM USER'S MANUAL

The following is a list of all the input and output parameters used in the model. The main program calculates the concentration of the introduced pollutant and prints out this concentration for each tidal cycle. The subroutines read in the physical parameters and the initial conditions considered for a specific case.

A. Main Program \((N, NTMAX, NTN, NTOUT)\) this computes the concentrations in each segment at each tidal cycle.

1. \(N\): the total number of segments, when \(N = 1\) is indexed outside the mouth.

   FORMAT (I5)

2. \(NTMAX, NTN\): the maximum number of tidal cycles to be run, the number of tidal cycles to be printed out.

   FORMAT (2I5)

3. \(NTOUT(I), I=1, NTN\): the tidal cycles that are to be printed out.

   FORMAT (10I5)

4. \(K, C2(K), K=1, N\): the reach number, the average pollutant concentration at that reach. This is an output parameter of the program.
B. Subroutine PHYDA

(1) TITLE: the name of the system to which the model is being applied.

FORMAT (1X, 35A2)

(2) NDG, NS, NAME: data group number, number of points in this group and the description of the contents. In order to exit the subroutine, set NDG > 99.

FORMAT (2I5, 30A2)

(2-a) Data Group 1

This group includes all the necessary geometric data.

(i) V(I), I=1, NS: the local low tide volume of each segment. The units are 10^6 ft^3. V(1) = 0, since it is outside the mouth.

FORMAT (7F10.0)

(ii) P(I), I=1, NS: the accumulated tidal prism volume upstream of the Ith transect. The first transect is located at the mouth. The units are 10^6 ft^3 per half tide.

FORMAT (7F10.0)

(2-b) Data Group 2

This group includes the lateral freshwater inflow into each segment. The units are in CFS.

(i) RLOCAL(I), I=1, NS: the local freshwater inflow into each segment. RLOCAL(1) = 0, since it is outside the mouth and is not used in the calculations.

FORMAT (7F10.0)
(2-C) Data Group 3
This group includes the value of the returning ratio, \( \alpha \), for each segment.

(i) AL(I), I=1, NS: the returning ratio. The value of \( \alpha \) may vary between segments, it is held constant in the present study.

FORMAT (7F10.0)

C. Subroutine INPUT
This subroutine reads the upstream freshwater discharge and the initial pollutant concentrations. Provisions are made for the expansion of the model by including water loads input. Default values are zero.

(1) TITLE: a brief description of the input parameters used in this subroutine.

FORMAT (1X, 30A2)

(2) NDG, NS, NAME: data group number, number of points in this group and a description of the contents. In order to exit the subroutine, set NDG > 99.

FORMAT (2I5, 30A2)

(2-a) Data Group 1
This data group includes the upstream freshwater discharge. NS=1 since the lateral freshwater flow for each segment has been considered in the subroutine PHYDA.

(i) DISCH: the upstream freshwater discharge

FORMAT (7F10.0)
(2-b) Data Group 2
This group includes the initial pollutant concentration in each segment.

(i) Cl(I), I=1, NS: in the present study, the initial condition is the average salinity at the mouth in parts per thousand. This is input only in the first segment, outside the mouth. Default values are zero.

FORMAT (7F10.0)

(2-c) Data Group 3
Additional pollutants may be introduced into specified segments of the river.

(i) K, QWAS(K), WBOD(K): READ I=1, NS the reach number, the waste flow in CFS and the pollutant load in pounds per day. Default values are zero.
REFERENCES


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