

# TRANSPORT PREDICTION IN PARTIALLY STRATIFIED TIDAL WATER<sup>a</sup>

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**ABSTRACT:** The essentials of hydrodynamic model application techniques and necessary supporting data are given for the situation of a partially stratified water body. The presentation is aimed at improving numerical predictions of tidal hydrodynamics, and is oriented toward somewhat experienced modelers. So as to guide the modeler, the subjects covered are arranged in the order in which they ideally would be addressed during the execution of a study. These subjects fall broadly under the headings hydrodynamic classification, model selection, model adaptation, model testing and calibration, and model verification and application. Meaningful and quantitative measures are needed to establish model performance, and to provide a basis for model intercomparisons and possible future setting of standards. Various quantitative measures are suggested. To encourage their use, it is recommended that providing a quantitative measure when comparing model data with observed data be a condition for publication. A number of research needs are also identified.

## INTRODUCTION

The Task Committee on Transport Prediction in Partially Stratified Tidal Water (TPPSTW) was formed to help improve and publicize current practices of predicting water motion and constituent transport in partially stratified coastal water bodies.

Modeling of partially stratified (sometimes called partially mixed) water bodies is one of the latest frontiers of computational coastal hydrodynamics. Partial stratification occurs when natural processes that cause lighter water to form over heavier water, such as surface heating or freshwater runoff, are counteracted by processes that cause mixing, such as turbulent kinetic energy generated by a mean flow, in such a way that a smooth vertical variation of density results. Examples of such conditions are found in many estuaries, e.g., Chesapeake Bay and San Francisco Bay, where freshwater inflows and tidal mixing interact. Because of the equal importance of several dynamic processes, scale laws that would allow accurate physical modeling cannot easily be obtained. These problems therefore lend themselves best to numerical modeling.

The numerical modeling of hydrodynamic transport in partially stratified

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estuaries is a highly complicated exercise. Partial stratification is evidence that vertical resolution is required and that density fields actively drive currents through gravitational forces. Thus, in contrast to more traditional tidal hydrodynamics, it is necessary to include an explicit description of vertical velocity structure and density distribution. The latter implies that a mass-transport component must be included in predictive models. Then, at a minimum, equations governing conservation of volume, conservation of momentum, and conservation of mass need to be solved. We use the term hydrodynamic transport broadly to describe water motion and mass transport associated with those processes that enter these equations.

Although focusing on the partially stratified situation, many of the recommendations contained herein are equally valid for the limiting cases of well-mixed and strongly stratified flows. In these situations, it may be warranted to apply simplified models (vertically integrated or two-layer) and to ignore the mass-transport equation when density is uniform. Considerable experience with such models has been accumulated in the literature (see, e.g., Leendertse 1967; Tracor 1971; Wang 1978; Lorenzetti et al. 1988). On the other hand, modeling of partially stratified flows usually calls for three-dimensional models or, at least, laterally integrated two-dimensional models, and very little guidance is available for embarking on such studies.

We attempt here to make a number of recommendations that are based on the committee's findings. It is the intent that these recommendations should be considered as a basis, or a set of minimum requirements, on which modelers can expand as appropriate. This paper is directed toward engineers and scientists at least somewhat familiar with the application of one- and two-dimensional vertically integrated hydrodynamic models, and beginning or in the process of carrying out a hydrodynamic study in partially stratified waters. Events in our presentation are arranged in a sequence that we feel is desirable for approaching a real problem. Basically, the first part deals with problem identification, or classification, and model selection. The second is concerned with model implementation in terms of discretization and data needs. The last part examines the actual application of the models via the processes of calibration and verification. It is hoped that this mode of presentation will be an aid to the modeler in organizing an investigation.

It is necessary to emphasize that accurate predictions of partially stratified flows are difficult, and require a multitude of judicious decisions, which currently cannot be based only on rigorous scientific facts or rules. A continuing and thorough technical review, preferably by a panel of unbiased experts and from inception to end of the project, should be considered an important component of any major modeling project. Additional review from the community can be achieved by widely disseminating reports.

The objectives of this committee are limited by necessity. We do not address the accuracy or numerical consistency with which the models describe physical processes, and thus do not make recommendations of particular models or model formulations. These are subjects considered by concurrent ASCE task committees on model verification and estuarine transport processes and their representation in spatially reduced and time-filtered models. It is assumed that the numerical formulations of the considered models produce reasonably accurate solutions to the governing equations and have been adequately verified against analytically tractable problems and prototype data for at least one estuary or coastal bay. An important research subject, treat-

ment of processes with scales too small to be resolved by the models (e.g. turbulence closures), is only briefly mentioned. It also is under review by other ASCE task committees.

### **CHOICE OF MODEL DOMAIN**

The world oceans and coastal areas are all connected and in theory behave as parts of one system. However, it is not practical to consider the entire system when dealing with a particular localized problem. It is indeed necessary to establish a limited domain within which processes can be described by a numerical model with reasonable effort. Even though computer speed is approaching levels at which one might consider global ocean models of reasonable resolution, the data requirements would be daunting and could not be met for many years to come.

When a limited domain is established, the interactions between the domain and the outside must be specified in the model as boundary conditions. Such conditions express the same conservation principles as the governing equations, although applied to a section rather than an infinitesimal differential volume. In theory, the conditions must accurately represent the sum of responses at the boundary, whether they arise from processes within or outside of the model domain.

In theory, the selection of model domain is then primarily dictated by availability of open-boundary conditions. Or in other words, with accurate boundary conditions, a model domain could be established with arbitrary shape and size. The reality is quite different because the premise of accurate and available boundary conditions is rarely if ever valid. Even if it were possible to measure all parameters in the prototype needed to specify conditions along contemplated boundaries, it would not result in accurate conditions for any meaningful model, which, as it implies, does not behave exactly like the prototype. This quandary is finally resolved by an axiom stating that the farther a location is removed from a boundary the less sensitive is its response to small perturbations in the applied boundary conditions.

The choice of model domain emerges as a compromise between cost, suggesting smaller domain, and reality, suggesting larger domain. The lesser weight should be assigned to cost in so far as economic, but erroneous, results are useless. Length scales of important processes can be used to guide the determination of model-domain size and distance to open boundaries, although existing or required measurements for prescribing boundary conditions also must be carefully assessed.

In some cases it is necessary to invoke a corollary of the influence axiom: the farther away from a boundary a system perturbation occurs, the less the boundary conditions will be affected. For example, when the effects of a proposed alteration to the physical system are investigated, the resultant changes in boundary conditions cannot be predicted. Hence boundaries must be removed far enough to allow use of existing conditions.

### **DESCRIPTION OF SYNOPTIC DENSITY FIELD**

The mixing of a vertically stratified system requires exchange of energy. Most often turbulent kinetic energy extracted from the mean flow in fric-

tional boundary layers is exchanged with potential energy resulting from mixing lighter water particles with heavier. Various parameters have been introduced to quantify the expected regime of stratification [e.g., the estuary number =  $(P_i F_o^2)/(Q_i T)$ , (TRACOR, Inc. 1971)], or the stratification parameter defined as the ratio: rate of turbulent energy dissipation divided by rate of gain of potential energy (Ippen 1966). When actual observations are available, the estuary may be classified using the system described by Hansen and Rattray (1966). In all instances, some knowledge of the density distribution is essential for determining the controlling processes in a particular problem.

Considering the low cost and effort required, a minimum of one synoptic-density-field survey should be made or equivalent information should be obtained from existing data. To remove tidal effects as much as possible, it is desirable to sample at slack. During slack water, currents are low, making water column sampling easier, but stratification may also be stronger than during other stages of the tide. The frequency of the sampling should be such that all density gradients in the vertical and horizontal are reasonably resolved.

A synoptic-density-field survey consists of density profiles collected at as many locations as necessary to determine the entire density field at a given short time interval. It is often useful to supplement such a survey with longer term records at selected locations. In many small estuaries, it is possible to use a small powerboat equipped with a field instrument to collect profiles of salinity and temperature. The usual procedure is to "run with the tide" such that the boat is following slack high or low tide as it moves through the estuary.

## **STUDY AREA CLASSIFICATION AND PROCESS SCALING**

The examination and analysis of available data, such as river flow, water surface elevations, wind, current, and salinity records, will help to classify the dynamics of the water body along with its range of variability. Some of these data are routinely collected in many estuaries and bays by federal and local government agencies as part of monitoring programs (e.g., National Ocean Survey, National Weather Service, U.S. Geological Survey, U.S. Army Corps of Engineers, U.S. Environmental Protection Agency, and state environmental agencies). One formal approach to determine the physical characteristics of the estuarine system is provided by the Hansen and Rattray classification scheme (1966). Their analysis shows the importance of maximum channel depth for stratification and density current circulation in an estuary. Models that do not adequately resolve the depths of the deeper channels of an estuarine system (i.e., averaging of the depth distribution has taken place) may have difficulty in predicting the correct degree of stratification and the strength of tidally averaged, near-bottom upstream flow. Similarly, the Hansen and Rattray theory indicates the importance of tidal dispersion in maintaining the salt balance of an estuary. Classifying a large water body at different locations can often indicate several regimes and important transport processes within an estuary, thereby helping to determine model needs. When the geometry is complex, or when sizable changes in freshwater runoff can be expected, allowances must be made in the classification and subsequent selection of model. Effort should be spent in acquiring and examining data at the early stages of a modeling effort so that

the most appropriate model can be selected and configured. For example, the discovery of the spring-neap differences in the salinity intrusion length and stratification at low river flow in the main channels of the Columbia River Estuary profoundly influenced the selection and development (including the numerical scheme) of a model that could handle the large vertical current shears and highly variable stratification of the dominant tidal dispersion process controlling the salinity intrusion (Hamilton 1984).

Scale analysis is another useful way of identifying important processes, which has, of course, been used extensively in design of physical models, for example. In this type of analysis, representative values of physical dimensions and dependent variables are estimated, and the relative magnitudes of terms appearing in the governing equations can be determined. Although numerical models often retain all terms in the equation of motion, they are rarely treated with equal importance. It is then useful to know what mechanisms can be expected to dominate, and therefore should be modeled with extra care.

## MODEL SELECTION

The distinguishing feature of partially stratified flows is the need for reasonable vertical resolution. In general, there is a coupling between mean horizontal motions and vertical structure so that flow features of certain scales do not appear unless the corresponding vertical structure is resolved. This leaves only two choices for stratified flow modeling: three-dimensional or laterally integrated two-dimensional models. In theory, vertically integrated models could be used if, *a priori*, the vertical structure were known. However, this is certainly not the case for predictions, leaving this alternative generally inadequate.

The choice of model is primarily dictated by its process-simulation capabilities and operational cost. Other factors may also be important, such as meeting the objectives of the modeling study without "overkill," and availability and practicality of obtaining data for calibration and verification.

Many relatively narrow, straight estuaries are suitable for laterally integrated two-dimensional models, whereas wide estuaries and embayments usually require use of three-dimensional models. Modeling of lateral variations becomes necessary in wide estuaries where both tidal pumping and dispersion produced by tidal trapping are important. Tidal pumping is an expression used to describe situations where the flow is distributed differently in a cross section during ebb and flood. The Coriolis force, bathymetry, and asymmetrical bottom friction are principal causes of tidal pumping. As a guide for coastal engineers, who perhaps are less familiar with the effects of the earth's rotation, the nondimensional Kelvin number can be used to provide a measure of the importance of Coriolis forces (see Appendix I).

Tidal trapping is a dominant dispersion mechanism in most estuaries (Fischer et al. 1979). Trapping is inherently a two-dimensional horizontal phenomenon, at least, because it arises from the temporary storage of water with its contained substances in side embayments, small branching channels, and shallow regions of an estuary, while the remainder of the flow proceeds along the estuary's major axis. If recapture of the stored volume is out of sync with the main flow, a longitudinal mixing occurs when the tide re-

verses. The dispersion induced by trapping can, in some sense, be parameterized through the use of model calibration; however, the resulting dispersion coefficients are not entirely satisfactory since they are applicable only under circumstances for which they are calibrated and lack universal validity. The wider the estuary, the smaller the range of validity for a set of coefficients. In addition, different wind conditions or freshwater discharges will produce rather different dispersion coefficients. The best way to include the effects of tidal trapping is to provide sufficient horizontal resolution so that the dispersion process is simulated in the model and not parameterized in a condition-specific manner. As a general rule, it may be stated that laterally integrated two-dimensional models are adequate if the time for lateral mixing is small compared to the time scales of the dominant longitudinal transport processes. In addition, loadings must be far enough away so that the location in a cross section where they are introduced is of small relevance. Otherwise, the penalty for using simpler two-dimensional models is a need to adjust model coefficients dependent on forcing conditions, and predictive ability may be sacrificed or reduced. For well-mixed conditions estimates of time scales for lateral mixing can be made (see, e.g., Fischer et al. 1979); however, little is known about this phenomenon in stratified flows. At present, the best approach is to carefully evaluate the synoptic data and only use laterally integrated two-dimensional models when lateral gradients are small relative to gradients to be modeled, at least in the primary region of interest. This means that if the primary interest is in the far field and the input from the near field can be adequately parameterized, then a laterally integrated two-dimensional approach may be warranted. Here, the near field refers to the region where significant lateral gradients occur.

The committee has not evaluated, and does not recommend, any particular models. A cursory review showed that far too many models exist to give a complete list of all. For more information, the reader may consult some recent references, on laterally integrated two-dimensional models (De Borne de Grandpré et al. 1981; Edinger and Buchak 1981; Perrells and Karelse 1981; Hamilton 1984). For recent monographs on three-dimensional models, the reader is referred to collections edited by Gray (1986), Heaps (1986), and Nihoul and Jamart (1987).

## **HORIZONTAL SCHEMATIZATION**

The design of a grid in which the physical properties and the process variables can be adequately described is a very important part of modeling and, at least to date, highly subjective.

The considerations involved in choosing the grid should include: anticipation of solution gradients, bathymetry and other physical properties, computational effort and cost, the purpose of model applications, and boundary conditions.

Some knowledge of solution gradients will be of immense help in choosing the grid-point separation. For variable grids, gradient characteristics can guide placement of grid points to achieve better resolution with fewest possible points. However, one of the pitfalls of variable grids is the introduction of distortion. In general, grids should be kept as uniform as possible to minimize possible numerical problems related to wave propagation and accuracy (in finite difference models, an additional requirement of orthogonality may

