# ABSTRACTS

## WORKSHOP ON MODELING PHYSICAL OCEANOGRAPHY OF PUGET SOUND

November 4-5, 1987

at

NOAA Western Regional Center
7600 Sand Point Way NE
Seattle, Washington

# FOREWORD

With the recent upsurge of interest in modeling the physical oceanography of Puget Sound, it seemed appropriate to have a workshop at which modelers and observational oceanographers could discuss how models might contribute to the understanding and prediction of physical processes in the Sound that bear on fundamental scientific issues as well as applied concerns such as water quality. The enthusiastic response to this suggestion is very gratifying. Puget Sound is such a diverse and complicated system that significant progress will require active collaboration between many investigators. It is hoped that the workshop will help to initiate and foster this collaboration.

One reason for choosing Puget Sound as a system to study is the rich set of ideas, insight and observations that is available for the Sound. These have been provided by a number of oceanographers over many decades, including Thomas G. Thompson, Clifford A. Barnes, Eugene Collias, Alyn C. Duxbury, Maurice Rattray, Jr., Glenn A. Cannon and Curtis C. Ebbesmeyer. We are pleased that several of these oceanographers have agreed to participate in the workshop.

The workshop was made possible through a financial contribution from the Pacific Marine Environmental Laboratory of NOAA and support from the U.S. Geological Survey and the University of Washington.

The Organizing Committee

Harold O. Mofjeld, NOAA
J. William Lavelle, NOAA
Roy A. Walters, USGS
Wen-sen Chu, Secretary
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# INTRODUCTION

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Over the last 35 years, analyses of oceanographic data collected in Puget Sound have opened our minds to the rich diversity of circulation modes that exist in this complicated estuary. These results clearly demonstrate the important roles played by wind forcing, mixing over sills, density and sea level changes at the seaward boundaries, nonlinear tidal effects, and freshwater runoff. The net result of these complex and competing forces is a range of circulation patterns that extend far beyond simple interpretations and offer a formidable challenge to our ability to predict the estuary's response to environmental stresses.

During the past decade, numerical techniques have begun to play a more central role in our quest for understanding. Numerical models simulating barotropic tides, regional mixing, and baroclinic phenomena have led to new insights into some of these fundamental processes. However in the past, our modeling efforts have been limited by the capacity of modern computer technology. Only recently has adequate computing power become generally available to begin to model in sufficient spatial and temporal detail the full range of physical processes found in Puget Sound.

We now find ourselves at an opportune point in time where hard won knowledge gained through expensive observational experiments can be greatly expanded and enhanced through relatively inexpensive numerical modeling studies. Indeed, we may be on the threshold of a renaissance in our understanding of this region, if we can successfully exploit, through active collaboration, the growing opportunities presented by today's micro-electronics revolution. Such a modeling capability, if properly developed and verified, will lead to a much needed ability to predict Puget Sound's environmental future, making possible wiser management and development decisions.

# CIRCULATION CHARACTERISTICS OF PUGET SOUND; FIELD OBSERVATIONS*

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Flow in the estuarine system that includes the glacially carved waterways of Puget Sound and the Strait of Juan de Fuca is dominated by tidal currents on which time varying currents caused by other effects are superimposed. While the overall system may appear as a large estuary, it is actually a complex composite of smaller estuaries with widely varying oceanographic characteristics resembling classic fjords (Saratoga Passage), coastal plain estuaries (Admiralty Inlet), salt wedge estuaries (Duwamish River), and embayments with weaker flows (Elliott Bay). The "main basin" of Puget Sound, extending between Admiralty Inlet and The Narrows, has characteristics in between the first two.

The main basin has received considerable study because of the proximity of major population centers and because it is the connection to the ocean with which most of the remainder of the system interacts. The residual circulation (tidal currents removed) is two-layered over the entrance sill and southward to somewhere around the north end of Vashon Island. The geographical location of this island forces primarily southward flow in East Passage with compensating northward flow on its west side. Recent current observations across several sections in both the one-layer and the two-layer regimes suggest residual fluxes about half those estimated earlier from midchannel observations. Annual variations may alter this by a factor of two being largest in winter and smallest in late summer.

Cross-channel observations including near-surface currents have been made at only a few locations. Modal analyses in both the one- and two-layer regimes show that variations in the residual circulation are caused by two physical processes. Wind effects dominate with about 50% of the residual energy and density driven deep-water intrusions account for about 20%. In addition, a third significant mode in the one-layer regime suggests some recirculation around Vashon Island. The wind mode shows energy concentrations both near the surface and at middepths. Earlier studies suggested possible deep changes in residual current profiles coincident with major north-south wind changes.

Earlier studies have documented that major bottom-water inflow events occur during neap tides when mixing over the sill is least and bottom gravitational circulation can develop. These intrusions propagate along the main basin as gravity currents with diminishing characteristics with distance from the sill. New observations on the inside and outside of the entrance sill show the onset actually occurs before the minimum in the neap tides. Simple model calculations suggest the onset is a result of fluctuations in the horizontal density gradient caused by salinity variations across the sill. Salinity changes outside the sill in the Strait of Juan de Fuca estuary may be caused by a combination of mixing over shoals and coastal wind effects penetrating the length of that estuary.

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* For reference, Puget Sound is defined by the U.S. Board of Geographic Names as those waters landward of the lines between Point Wilson to Point Partridge and across Deception Pass. This outer limit also makes sense oceanographically because it is located at about the shoalest part of the Admiralty Inlet sill.

# A BATHYMETRIC DATA BASE FOR PUGET SOUND

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The flow in an estuary is determined in large part by its physiography. To aid oceanographic investigations of Puget Sound a bathymetric data base is being developed at PMEL. Depths obtained from nautical charts suffer from a number of drawbacks which include a bias toward shallow depths in any given region due to navigational requirements, the need for digitization, wide and irregular spacing, and inappropriate map projections. Our goal is to use all available soundings to produce digital, regularly gridded depths for Puget Sound in a planar Cartesian coordinate system tangent to the earth's ellipsoid.

Over 1,000,000 soundings recorded from 1930 to 1967 in the Strait of Juan de Fuca, Haro Strait, Rosario Strait and Puget Sound by the National Ocean Service have been obtained on magnetic tape from NOAA's National Geophysical Data Center. Additionally soundings on punched cards from the Hydrographic Section of NOAA's Pacific Marine Center have been used to fill some data gaps in Admiralty Inlet and Hood Canal. The latter are intermediate hydrographic products not intended for general release and as such contain some errors in depth and position. The location of the shoreline is not included in these data sets since soundings are taken from ships which by their very nature cannot navigate at the land/sea boundary. Consequently the shoreline, the location of Mean High Water, has been digitized from nautical charts.

The data contain rare, but potentially devastating errors. Soundings shallower than Mean Lower Low Water, the datum, are allowed, but by NOS convention this fact should be encoded in a separate field of each data record. This is not true for a few soundings which are discarded as a first step. Some soundings which appear landward of the shoreline due to temporal changes in its location or due to position errors are also discarded. The automatic detection of such points is not a trivial programming task!

The hydrodynamic equations governing fluid motion are usually formulated and solved in Cartesian coordinates. For estuarine problems the area of interest does not cover more than a few degrees of latitude; hence an f-plane approximation is appropriate in which the latitudinally varying Coriolis parameter is held fixed at its value at the point of contact with a plane tangent to the earth. The map projection coincident with this geometric idea is the oblique azimuthal stereographic projection. This is simply the globe projected onto a plane tangent to the earth at one point (hence azimuthal) which is not at a pole (hence oblique); the source point of the projection is the tangent point's antipode (hence stereographic). This projection has 2 advantages: (1) angles and local shapes are preserved, i.e. it is conformal, and (2) distortions over estuarine scales are slight. The Seattle Space Needle has been chosen as the point of tangency for our applications.

The soundings in each $250 \times 250$ m square on the projection are fit by a plane using the least squares method. An individual data point is discarded and the plane is recomputed if the vertical distance between the two exceeds a threshold value (currently 50 m).

Plan-view, color diagrams of the depths illustrate vividly the bathymetry of Puget Sound. Similar diagrams of the bottom slope show the glacially carved nature of the region. The side walls slope steeply downward to the relatively flat channel floors.

Banks in the Strait of Juan de Fuca are particularly well delineated in this representation. The root-mean-square error of each planar fit is an indication of the bottom roughness. The channel walls are rough, and the bottoms are smooth reflecting the effects of sedimentation.

Future plans include the incorporation of more recent bathymetric data to fill gaps and the provision for interactive facilities in which depths along user-specified transects can be displayed and output to data files for further analysis.

# OBSERVED TIDES AND TIDAL CURRENTS IN PUGET SOUND

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Strong tides and tidal currents dominate the observations of sea level and currents in Puget Sound and play important roles in the physical oceanography of the region (Rattray, University of Washington, 1954; Mofjeld and Larsen, 1984). They are fundamental to such major processes as the water exchange through Admiralty Inlet and the mean circulation around Vashon Island. The circulation and distributions of water properties in Puget Sound are strongly influenced by the large weekly, monthly, seasonal and interannual variations in the tidal motions.

Extensive observations indicate that the tidal motions enter Puget Sound primarily through Admiralty Inlet with a small contribution through Deception Pass that is locally important in northern Whidbey Basin (the tidal transport through Swinomish Channel is insignificant.) The tides form nearly standing waves in the major basins with large areas of relatively constant amplitudes and phases in the tides. Observed cross-channel variations in the tides are generally very small. The constricted channels connecting the basins are sites of major changes in the tides, strong tidal currents and high tidal dissipation. The total 8.08 $km^3$ tidal prism between mean lower low water and mean high water is 4.8% of Puget Sound's total volume (168.7 $km^3$) below mean lower low water.

The diurnal and semidiurnal tides are comparable in Puget Sound. Due to the semidiurnal, quarter-wave node in the eastern Strait of Juan de Fuca, the tide at the entrance (Port Townsend) to Admiralty Inlet is mixed-diurnal (Type = 1.44) with a diurnal range of 2.6 m. Moving upestuary from this entrance, the tides in Puget Sound become progressively more mixed-semidiurnal (Type = 0.97 at Seattle and 0.75 at Olympia); the tides also increase in diurnal range (3.4 m at Seattle and 4.4 m at Olympia) due primarily to a 2.2-fold increase in semidiurnal amplitude. In contrast the diurnal (K1) tidal amplitude increases only 16% between Port Townsend near the main entrance of Puget Sound and Olympia at the southern terminus. Because Puget Sound is so deep, the tidal range is comparable with the water depth only very nearshore, at the ends of undredged embayments and over the extensive tidal flats in Skagit Bay and northern Port Susan.

A comparison with tidal theory suggests that increases in semi-diurnal tidal amplitude and phases between the Main Basin and the Southern Basin occur because The Narrows and the Southern Basin form a Helmholtz resonator. One implication for modeling the tides in this region is that the length, width and depth of The Narrows must be resolved properly to simulate the semidiurnal tides correctly.

The observed tidal currents in Puget Sound show much more spatial variation and are more semidiurnal (Type = 0.5) than the tides. The strongest tidal currents (>1 m/s) occur in the channels connecting basins (e.g., Admiralty Inlet, Deception Pass, The Narrows, Hammersley Inlet) and sub-regions of the Southern Basin (e.g., Nisqually Reach, Dana Passage). Locally strong currents are also found near points of land such as Three Tree Point in East Passage. The weakest current amplitudes (<0.1 m/s) are found in side-embayments like Elliott Bay and Commencement Bay and in terminal channels like Budd Inlet and Lynch Cove. At mid-channel where most current observations have been made, the current ellipses are narrow with the major currents oriented along-channel. Broad current ellipses do occur at junctions where several channels meet, such as the northern end of the Main Basin, and in embayments like Elliott Bay and Commencement Bay that contain weak tidal eddies (Sillcox, Geyer and Cannon, 1981).

The few detailed current sections that have been observed across channels in Puget Sound indicate that there can be substantial cross-channel variations in the amplitudes of the tidal currents. The M2 current amplitude observed between Port Monroe (Bainbridge Island) and Meadow Point (Seattle) in the central Main Basin increases eastward from 10 cm/s to 23 cm/s. A factor of three change in M2 current amplitude is observed in a section off Three Tree Point in East Passage with the greatest amplitude occurring near the point. The current phases show much less cross-channel variation with earlier phases nearshore.

In the high-current channels like Admiralty Inlet, the bottom boundary layer extends over the entire water column with tidal current amplitudes and phase lags decreasing with depth from the surface (Mofjeld and Larsen, 1984; Mofjeld and Lavelle, 1984). Elsewhere the tidal currents tend to be relatively independent of depth above a thin bottom boundary layer except for local topographic steering of the direction.

The tidal currents in Puget Sound exhibit a large number of small-scale features. Sharp tidal fronts (tide rips) with large surface convergence occur in Puget Sound where strong currents from one channel enter another channel with weaker currents. Tidal fronts are also seen at the edges of tidal eddies that form downstream of points of land and move offshore when the current reverses (Jamart and Winter, 1978; Shi, 1978). High-frequency fluctuations in the observed currents (as well as results from the physical and vertically-averaged numerical models) indicate that these eddies are common features of Puget Sound.

In Admiralty Inlet tidal excursions can carry water tens of kilometers when the diurnal and semidiurnal excursions are in phase. Tidal excursions of 5 km or less are more common off Seattle in the Main Basin. A net tidal transport (residual current) around Vashon Island is observed to be a major component of the circulation in the southern Main Basin. The strength of the mean transport is probably related in part to the northward jet entering Colvos Passage from The Narrows during ebb (Cannon, Laird and Keefer, 1979). Similar residual circulations may occur around islands in the Southern Basin.

An example of applying tidal results to the understanding of physical processes in Puget Sound is an intrusion index derived from tidal currents in Admiralty Inlet (Mofjeld, in preparation). Based on the estuarine Richardson number (Fischer, 1972) in which the cubic power of the tidal current speed appears in the denominator, the index identifies periods of low tidal mixing when intrusions of new water are often observed to enter the Main Basin (Geyer and Cannon, 1982). Multi-year time series of the index show that in a typical year, periods of lowest tidal mixing occur monthly near the equinoxes whereas summer and winter have extended periods of relatively high mixing. Every fourth or fifth year, Admiralty Inlet has high tidal mixing throughout the year.

# METEOROLOGICAL SETTING OF THE PUGET SOUND REGION

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The winds of the Puget Sound region are produced by the complex interaction between the large-scale synoptic flow, the substantial topography of the region, and local diurnal circulations. On the synoptic scale the winds impinging on the Washington coast are controlled by the intensity and movement of the subtropical East Pacific High and the Gulf of Alaska Low as well as transient disturbances that move through the region. This synoptic scale forcing tends to establish southerly flow in the Sound during the winter and northerly flow during the summer.

The large scale forcing is in turn profoundly modulated by the Olympic and Cascade Mountains and by land-water contrasts in surface heating and roughness. For example, when the winds on the Washington coast are from the west or northwest a trough and convergence zone form in the lee of the Olympics. The result is a sharp wind shift line and an area of enhanced cloudiness and precipitation. Lee troughing contributed to high winds over northern Puget Sound on February 13, 1979 that resulted in the destruction of the Hood Canal Bridge.

Diurnal circulations, such as sea/land breezes and mountain/valley winds, also have a substantial effect on low-level winds over the Puget Sound region. Such diurnal circulations are the origin of the well-known "Sound Breeze" that brings increased northerly flow to the northern Sound during summer afternoons.

# PRELIMINARY OBSERVATIONS OF TURBULENCE IN PUGET SOUND AND ADMIRALTY INLET

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During the past decade random turbulence measurements have been obtained in local waters by the microstructure group APL/UW. Comparison of these tentative measurements with the results of much more intensive work in the open ocean, demonstrates strong mixing and may provide clues as how to parameterize the mixing in numerical models.

An hour before maximum ebb tide in Admiralty Inlet we found turbulence as intense as that in the high-shear core of the equatorial undercurrent, with dissipation rates, $\varepsilon$, exceeding $10^{-6}$ W kg$^{-1}$. Geyer and Cannon (1982) estimated dissipation rates of $4 \times 10^{-5}$ W kg$^{-1}$ over the sill due to the M2 tide. This is about 10 times larger than we observed, but our data are far too sparse for any sort of mean value. Rather the observations demonstrate dissipation extraordinarily high, as was predicted.

For the time of our measurements, tide tables gave maximum surface currents of 1.2 m s$^{-1}$. Two Expendable Current Profiler (XCP) records revealed 0.7 m s$^{-1}$ between 10 m and the bottom just below 60 m. The profile was well-stratified in the mean, but contained several mixing zones, with maximum overturning scales less than 5 m. In one profile the gradient Richardson number was approximately 0.05 in the mid-water mixing zone.

From these data, at least, the mixing occurred in a stratified profile and it was not appropriate to estimate the Reynolds number, Re, from the channel depth. Grant, Stewart, and Moilliet (1962) used a current of 1 m s$^{-1}$ and a channel depth of 100 m to obtain $Re \propto 10^8$ during the pioneering turbulence measurements in Discovery Passage. The same approach in Admiralty Inlet yields $Re > 6.6 \times 10^7$. Maximum turbulence scales were approximately 5 m, however, not 60 m.

Vertical eddy coefficients estimated from the Admiralty Inlet observations will be compared with those from the oceanic thermocline.

Observations in Puget Sound routinely find $\varepsilon$ of at least $10^{-8}$ W kg$^{-1}$ in the upper 100 m, at least a decade above typical levels in the open ocean. Observations of high frequency acoustic backscatter by Marshall Orr (personal communication) demonstrate a rich variety of processes producing mixing, including internal waves generated by tidal flows over bottom topography.

Microstructure profiling, acoustic Doppler current profiling, moored currents and densities, and bottom-mounted turbulence platforms are now routine measurements for research groups situated on Puget Sound. Coupled with well-formulated numerical models, using these tools to study key mixing areas can lead to a major increase in understanding the dynamics of the Sound. Because this has not been done before in other estuaries, this could also be a major milestone in basic research.

# A REVIEW OF ANALYTIC CIRCULATION THEORY APPLIED TO PUGET SOUND

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Until the advent of numerical models, analytic circulation theory was the only theoretical tool for studying the physical oceanography of estuaries. Focusing on estuaries with very simple shapes, the theory provides formulas for the longitudinal and vertical distributions of tidally-averaged currents (circulation) and water properties (i.e., salinity) that are solutions to dynamic equations based on steady balances between a few dominant processes (Dyer, 1973; Officer, 1976). The formulas are often derived from similarity theory which requires particular dependences of quantities like the eddy diffusivities on depth and location. They are fit to observations to infer dynamic quantities some of which, like upwelling velocities and currents when only salinity was observed, cannot be or were not measured directly. The theory also provides ratios of parameters that can be used to predict how an estuary will respond to changes in river runoff, tidal mixing, wind stress and other external forcing. It is the basis for the dynamical classification scheme (Hansen and Rattray, 1966) of estuaries that is used today.

Estuarine theory has been applied to several areas in the Puget Sound region. The literature contains similarity models of fjord-type (Type 3) estuaries for Whidbey Basin, the Main Basin and Hood Canal (Winter, 1973). Admiralty Inlet has been typed as a coastal plain (Type 2) estuary (Barnes and Ebbesmeyer, 1978) and the Strait of Juan de Fuca as having fjord dynamics (Hansen and Rattray, 1966). The Duwamish River has been modeled as a salt-wedge (Type 4) estuary (Rattray and Mitsuda, 1974) and the entire Puget Sound as an efflux/reflux network of advective reaches and mixing zones (Cokelet and Stewart, 1985; Cokelet, this Workshop).

Similarity and other analytic models require extensive data sets for tuning and validation. The models treat tidally- and width-averaged distributions of currents and water properties and predict the detailed variations with depth and along-channel distance. Three-dimensional, tide-resolving observations (as well as ancillary wind, runoff and entrance salinity data) are required to test the basic assumptions of the model. Thus far in Puget Sound, such a data set does not exist. Although some detailed observations have been made across a few sections of the Sound, models have been most often tuned to and compared with mid-channel observations. It is an open question as to whether the models have been tuned to adequate data sets.

A major improvement in analytic theory (and numerical models of estuaries) will occur when more realistic formulations are found for mixing and dispersion processes. The gap between the greatly simplified estuaries treated by analytic circulation theory and Puget Sound, with its highly time- and spatially-varying dynamics and complex topography, is a major justification for applying numerical models to the Sound. Still, analytic circulation theory provides an essential conceptual foundation. The theory will remain a valuable tool for understanding the basic dynamics and long-term behavior of Puget Sound.

# SOME CONSIDERATIONS FOR AN ENLARGED PHYSICAL MODEL OF PUGET SOUND

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Physical hydraulic models have been used successfully for a long time to predict the response of estuaries to changes such as dredging, land fills, constrictions, and changes in flow. From an engineering standpoint, model predictions of tidal ranges and phases, current velocities, circulation patterns, and salinity intrusion have generally been considered to be reliable in evaluating such proposed changes.

Physical, as well as mathematical, models require proper boundary conditions. The main considerations in determining limits of an estuary model are the upper reaches of the estuary and the "ocean", which are boundary condition control points. The "ocean" area contains the tide generator and (in typical cases where salinity distribution is important) provisions for maintaining a constant salinity, and its shape and extent are dictated by current patterns at the month of the estuary. The landward end generally coincides with the upstream limit of tidal motion. Freshwater inflow hydrographs constitute an additional boundary condition.

The verification process may be carried out for a single tide condition which approximates an average condition for the time during which field data to be used for model verification were obtained, or for a single tidal constituent (typically the $M_2$) or combination of constituents obtained from harmonic analysis of the field data. The first stage of verification is concerned with reproduction of tidal ranges and phases, and the second with the reproduction of current magnitudes and directions. These processes may require an extensive initial field data acquisition program. Verification of both lateral and vertical distributions of velocities is obtained by trial local adjustments of boundary roughness elements in the model, analogous to adjustment of resistance coefficients in mathematical models. Salinity verification may involve only reproduction of conditions obtained during quasi-steady conditions of a single tidal cycle under average freshwater inflow conditions. Mechanical methods are often required to obtain proper vertical distribution of salinity in partially mixed estuaries; the procedure is analogous to adjusting diffusion coefficients in mathematical models.

Geometric distortion is necessary in physical models of estuaries from the standpoints of both economics and fluid mechanics. Tidal motions and freshwater inflows are based on Froude law relationships. Most models in the United States have been of relatively shallow estuaries. The most common practice in the United States has been to use a vertical distortion of 10 in tidal models.

The Chesapeake Bay Model, constructed and operated in the 1970's by the Corps of Engineers, is selected to illustrate a 10:1 distortion ratio model of a broad, shallow estuary. The model and its construction, appurtenances, and operating procedures are described, and field data analysis used in the model verification process is discussed. A major reason for constructing the model was to predict effects upon salinity distribution throughout the bay caused by deepening existing navigation channels along the axis of the bay. Salinity varies markedly over the bay, both vertically and longitudinally.

Puget Sound is much deeper, and variations in salinity are much smaller. Therefore it is proposed that a physical model of Puget Sound be a single fluid model, with no consideration of attempting to simulate salinity distribution in the model. Consequences of choosing various possible combinations of horizontal and vertical scale ratios for a Puget Sound model with boundary conditions at Admiralty Inlet and Deception Pass are discussed. The existing Puget Sound model in the Department of Oceanography at the University of Washington is used as a basis for comparison.

The final comments apply to both mathematical and physical models. The purpose of the model must be recognized; what scientific and/or engineering questions are to be asked of it? For example, is the model to be used for investigating global or local problems? If the ultimate objective is to use the model as a tool in water quality studies, effects of model distortion or dispersive transport must be kept in mind. Limitations of the model must be recognized so that it is not asked to answer problems for which it was not designed.

# MODELING APPROACHES: NUMERICAL MODELS

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In a general sense, numerical models are tools with which to understand the behavior of a field site - Puget Sound in this case. From a given input, the model predicts an output that hopefully agrees with observational data. However, even when there is disagreement, much can still be learned about the field site usually through recognition of additional processes at work.

There are two broad, overlapping categories of numerical models: statistical and deterministic. In the statistical model, an output is derived from a given input through an objective analysis based upon observational data, such as a regression analysis between salinity and freshwater inflow into an estuary. In the deterministic model, an output is derived from a given input through a set of physical laws applicable at the site. These laws are usually cast in the form of differential equations describing the force balances and the conservation of mass. In many cases, the process submodels contained within a deterministic model are statistical in nature. The primary emphasis in this discussion is placed upon deterministic models.

The types of processes that a numerical model can resolve are dependent upon the time and space scales inherent in the model. For those models that march forward in time using discrete time steps, the step size must be much smaller than the time scale of the process to be resolved. On the other hand, motions in estuaries range in time from gravity waves (seconds) to geologic scales (Ma). For practical reasons, the minimum time scale for many models is that of the tides. The maximum time scale is determined by the length of the simulation, usually from weeks to a month. For longer periods, time-averaging the governing equations and other methods can be used. One method, in particular, is to transform the governing equations into the frequency domain from the time domain. In this manner, tides and long-period motions are treated separately.

As with the time domain, the space domain must be discretized with a certain step size. In a manner similar to time steps, the size of the space step determines which processes can be resolved. The other important factor is the spatial dimensions included in the model, where the number of dimensions can vary from zero to three. Zero-dimensional models (box models) are averaged in the study of interactions in the water column, for instance bio-chemical interactions.

One-dimensional models are averaged over either the width and depth of the water body, or over the surface area. They are useful in those cases where important processes do not depend upon the lateral variation of the variables. The width- and depth-averaged model is used to study the tides and solute transport in branched estuaries. The area-averaged model is used to study stratification in locations where horizontal advection is not important.

Two-dimensional models can be averaged over either depth or width. The depth-averaged model can be used to study a wide range of problems where the vertical variation of the important variables is reasonably well known. Examples include the simulation of tides, residual flows on long time scales, and the depth-averaged effect of wind stress. The laterally averaged model can address stratification, density-induced circulation, and other flows with strong vertical variation.

Three-dimensional models are only limited by their ability to resolve subgrid scale processes. Typically, these limitations include an inability to adequately refine all spatial dimensions because of finite computational resources. Nonetheless, these models are used on a wide range of important and difficult problems. One problem of particular merit is the calculation of long period (residual) currents in a stratified estuary that has large variations in both width and depth. In this case, both lateral and vertical variations in the physical processes are important.

As yet (and not expected to occur), a single model will not answer all the questions of interest in estuaries. The choice between models ultimately involves a choice based upon the relative importance of the various processes and how these processes are reproduced in the model.

# PRODUCTION OF A FJORD BASIN'S PYCNOCLINE BY TIDAL MIXING OVER A SILL

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The vertical profile of density in Puget Sound's Main Basin (Admiralty Inlet to The Narrows) has been examined using field observations and a simple, algebraic model.

The field observations consist of density profiles obtained using water bottles and conductivity-temperature-depth (CTD) sensors. These data show that, on average, the density profile can be separated into three depth ranges defined by changes in the slope of the vertical gradient: 1) 0 to 5-10 meters, containing plumes or patches of local river water; 2) 5-10 to 58-100 meters, containing water originating in The Narrows; and 3) greater depth, containing water originating in Admiralty Inlet.

Water in the middle depth range contains the pycnocline of interest, and is further defined by a density staircase in which most of the density change is associated with sharp steps. In the layers between the steps the vertical gradient equals that found in Colvos Passage. Using the density gradient as a tracer, as well as previously developed circulatory models, it is hypothesized that the layers originate from intense vertical mixing by tidal currents in The Narrows at the head of Colvos Passage. Waters from the source basins lying to either side of The Narrows feed at various times during a tidal day into The Narrows. The intense mixing produces batches of comparatively homogeneous water which quickly travel through Colvos Passage. As the batches emerge from Colvos Passage into the Main Basin they decelerate and sort themselves according to density thereby forming the pycnocline.

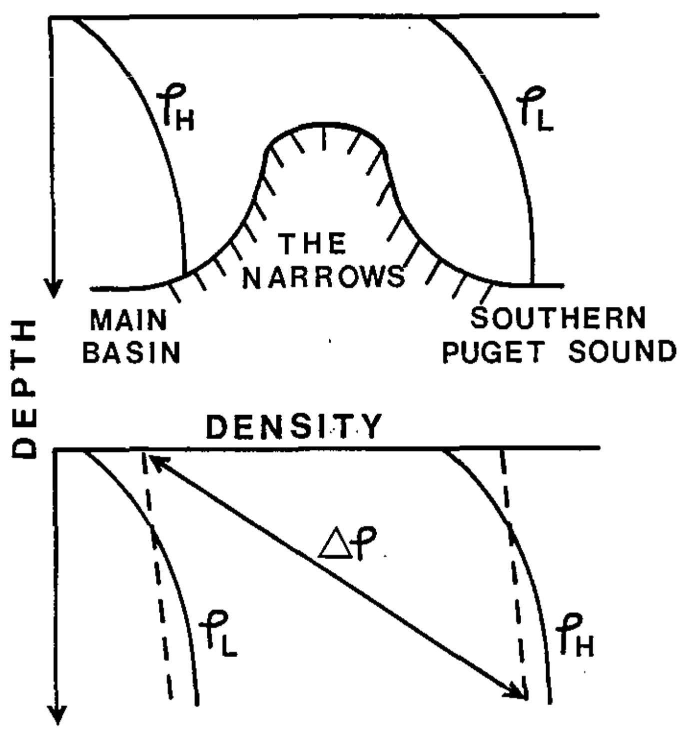
The density difference across the pycnocline was derived as follows. Assume that water in a source basin is vertically mixed in The Narrows such that after mixing the water column has a density stratification observed in Colvos Passage (unmixed profiles represented by solid lines become mixed as represented by dashed lines in the Figure). Furthermore, because 75% of the variance of a given density profile in Colvos Passage can be represented by linear approximation, assume that the density profile after mixing is linear with depth. Then the density range across the pycnocline equals the density range between batches of water drawn from the two source basins. The lowest density will occur at the water surface after water from the source basin having lowest mean density ($\rho_L$ in Southern Puget Sound) is vertically mixed, and the highest density will occur at the bottom of the water column after water from the source basin having highest mean density ($\rho_H$ in the Main Basin) has been mixed. Applying these assumptions, the density range across the pycnocline ($\Delta\rho$) is

$$\Delta\rho = \overline{\rho}_H - \overline{\rho}_L + b_c h_c \ , \qquad (1)$$

where $b_c$ and $h_c$ are the density gradient and bottom depth in Colvos Passage, respectively, and the overbars denote averages over the water column.

Monthly averages were computed for the terms of eq. (1). The observed difference in density across the pycnocline represented by the left-hand-side agrees well with the difference predicted by the simple formulation (correlation coefficient, r = 0.85).

This work is relevant to waste discharge. The density layers lie within discrete parcels of water. Since the pycnocline extends through much of the Main Basin from Admiralty Inlet to The Narrows, the water parcels are also a ubiquitous feature of the Main Basin. Shortly after waste effluent leaves an outfall much of it can become trapped in water parcels. In an experiment off West Point, parcels contained unexpectedly high effluent concentrations. To minimize the consequences of the trapping mechanism, outfall diffusers should be designed to achieve the highest possible dilution before waste effluent enters the Main Basin.



## THE EFFECTS OF STOKES DRIFT AND LONGITUDINAL VARIATION IN PARAMETERS ON THE MEAN SALINITY DISTRIBUTION AND CIRCULATION IN CLASS 1 AND 2 ESTUARIES

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A model of estuarine transport processes has been developed that includes the following features not found in previous analytical models:

(i) A Lagrangian-mean formulation for the tidally-averaged property distributions in estuaries. This modification provides an explicit accounting of the tidal contribution to the net particle or Lagrangian fluxes of matter in the estuary.

(ii) Arbitrary longitudinal distributions of net fresh-water inflow, estuary width and depth, and turbulent eddy coefficients. This generality allows the effect of sills on the overall estuarine circulation pattern to be determined.

(iii) An explicit expression for the tidal "shear-effect", giving the tidally-induced longitudinal "diffusive" flux of salt. In the Lagrangian-mean formulation this flux is given by the temporal correlation between the cross-sectional gradients of tidal longitudinal displacement and the tidal variations in the corresponding vertical and lateral component of the turbulent fluxes.

Based on the desire to explicitly characterize the Lagrangian motions of water particles, averaged over the tidal cycle, the model incorporates Stokes drift, and the associated tidal fluxes of momentum and salt, into the equations by replacing the traditional Eulerian dependent variables with the generalized Lagrangian-mean variables defined by Andrews and McIntyre (1978). The resulting equations describe the properties of the Lagrangian-mean dependent variables in terms of the usual Eulerian independent space and time variable and are the well-suited for the description of estuaries with strong tidal currents.

A solution of the governing equations governing the model has been obtained by retaining arbitrary longitudinal variation in all the variables and expanding the dependent variables in terms of (1/M), where M is a mixing-parameter expressing the relative importance of tidallyinduced turbulent mixing. This solution provides the longitudinal and vertical dependencies of the tidally-averaged mean-Lagrangian current and salinity distributions for estuaries with realistic geometries. The inclusion of these tidal effects, in addition to the longitudinal variations in the governing parameters, provides a more complete understanding of the factors controlling the behavior of partially stratified estuaries than has hitherto been presented.

Application of the model results to the Admiralty Inlet - Main Basin system explains the change in the circulation that has been observed by Ebbesmeyer and Barnes (1980) and Ebbesmeyer, Coomes, Cox, Helseth, Hinchey, Cannon and Barnes (1984) at the transition between the deep basin and the sill. Corresponding to this change in circulation between the deep basin and the sill is a change in the mechanism responsible for the horizontal salt flux. Whereas in the main basin, the salinity is maintained against the fresh water dilution by horizontal advection of the two-layer flow, over the sill the two-layer advective salt flux is only a small fraction of the salt flux resulting from the horizontal tidal diffusion. The clear implication of this result is that horizontal pollutant fluxes, in the total Puget Sound system, cannot be determined by advective fluxes alone but the horizontal "diffusive" fluxes are important and must be considered.

# RESIDUAL CIRCULATION IN ESTUARIES WITH COMPLEX TOPOGRAPHY

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In this paper we discuss the application of existing analytical models for shallow estuaries of simple form to systems such as Puget Sound with complex topography and spatially-variable mixing processes. In these models, finite-amplitude barotropic and internal wave theory is used to calculate tidal velocities, the salinity distribution, and the non-linear generation of the residual flow by barotropic and baroclinic mechanisms. Essential to these calculations is the correct representation of the interaction of stratification and vertical mixing. Three basic situations occur in shallow estuaries. In highly-stratified salt-wedge systems, the dominant mixing process bringing about the exchange of salt and freshwater is instability of the interfacial layer. Bottom-boundary-induced mixing predominates in weakly-stratified flows. Neither of these processes is active in partially-mixed systems, and a variety of mechanisms have been proposed. Of these possibilities, random internal wave interactions are the most important factor in partially-mixed estuaries with small depth-to-width ratios. Model results show that each of these dominant mixing processes corresponds to a different type of residual circulation. This theory also leads to a new classification system for shallow estuaries, based on the strength of the dominant baroclinic and barotropic mechanisms driving the residual circulation.

Extension of the above modeling techniques to Puget Sound requires three developments to account for circulation effects over topography and in deep basins. The first is the calculation of the barotropically-forced, internal tide in a deep basin with a shallow upper layer. Depth and width variations may be included by dividing the system into a series of sections, each of uniform width and depth, as done by Bronkers (1964) for the barotropic tide. The second is determination of the dominant mixing processes in Puget Sound and development, if necessary, of algorithms suitable for use with the internal tide model. In this regard, the existing algorithms for weakly and highly-stratified (salt-wedge) estuaries could be applied, respectively, to constrictions and sills (e.g. Admiralty Inlet and the Tacoma Narrows), and to highly-stratified basins wherein mixing processes at the adjacent sills do not radiate into the interior via internal waves (perhaps Whidbey Basin). Furthermore, Farmer and Smith (1978) have represented analytically the propagation of finite amplitude internal waves released at the change of the tide from a sill in Knight Inlet. Their analysis allows definition of a mixing algorithm which may be useful in Puget Sound or other fjords. Finally, because the density field in the deeper basins of Puget Sound is in large part the result of mixing at sills and subsequent advection of mixed water, proper boundary conditions between sections of the estuary model must be formulated for the density field.

# THE ANNUAL MEAN TRANSPORT AND REFLUXING IN PUGET SOUND

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The task of predicting the long-term build-up of pollutants in Puget Sound is becoming more important with increasing urbanization. Two logical ways to attack the problem are to study historical data sets and to engage in long-term modeling. The most commonly available oceanographic data tend to be temperature and salinity observations which provide no direct information about pollutants. Modern, time-dependent, multi-dimensional computational models have the potential for being up to the task especially if tuned to a particular estuary, but they are rarely run over simulation periods of several years due to their cost. This leaves the simple box model based upon hydrographic observations as an attractive alternative.

Puget Sound consists of a series of deep, stratified reaches separated by shallower sills and junctions where the mixing between water masses occurs and most of the rivers enter. On an annual time scale the transport in each reach can be modeled as a steady two-layer advective flow. These flows intermingle in turbulent mixing zones where the flow from any incoming layer can be split into two parts: an efflux fraction which continues on into the next reach, and a reflux fraction which recirculates into its original reach.

Cokelet and Stewart (*J. Geophys. Res., 90*, 7287-7306, 1985) were the first to put forward a general theory defining the efflux/reflux fractions as coefficients in the mass balance equations for conservative tracers, of which fresh water and salt are two examples. They expressed the coefficients in terms of the appropriate flux-weighted salinities and mass transports in the reaches, and they related the long-term concentrations of other conservative tracers to the circulation via the efflux/reflux formulation. Furthermore they defined the mean tracer age, the relevant time scale in a recirculating system, and related it to the efflux/reflux coefficients. For a multiple junction mixing zone at which more than two reaches meet, Cokelet and Stewart demonstrated that the knowledge of only two tracer concentrations (for example, fresh water and salt) was insufficient to determine uniquely the efflux/reflux coefficients. They proposed an entropy maximization technique which is maximally noncommittal with respect to the missing tracer information as one rational way to resolve the uncertainty.

In a recent paper Cokelet, Stewart and Ebbesmeyer (to be submitted to *J. Geophys. Res.*, 1987) have calculated the flux-weighted salinities and volume transports necessary to apply the efflux/reflux theory to a nine-reach model of the Strait of Juan de Fuca and Puget Sound. The flux-weighted salinity is obtained from an integral of the annual mean salinity weighted by the current velocity over the depth and width of each reach layer. The salinity data comes from the extensive University of Washington hydrographic observations of 1951 to 1956, and the velocity profiles stem from composite fits to currents measured mostly in the 1970's.

The annual landward and seaward transports have been calculated from the salinities and runoffs via Knudsen's equations. This is the first time that: (1) the principal reaches of the Strait and the Sound have been considered simultaneously, (2) the annual averages have been computed over several years, and (3) the uncertainties in the transports have been estimated. In the Strait of Juan de Fuca the annual transport averages over 100,000 $m^3/s$, but it decreases to about 40,000 $m^3/s$ at the entrance to Puget Sound. The transports are small (<7,000 $m^3/s$) and steadily decrease up Hood Canal and Saratoga Passage. However up the main axis the transport decreases to about 14,000 $m^3/s$ off Point Jefferson but then rises to 32,000 $m^3/s$ in East and Colvos Passages before decreasing again to 15,000 $m^3/s$ off Gordon Point and to 5,000 $m^3/s$ off Devils Head. With few exceptions the inferred transports agree well with estimates derived from scattered, shorter term current observations and from oxygen utilization techniques.

Ebbesmeyer and Barnes (*Estuar. Coastal Mar. Sci., 11,* 311-330, 1980) first presented evidence that about two-thirds of the seaward-flowing water entering Admiralty Inlet refluxes landward into the main basin. Preliminary results from the present analysis utilizing a more exact theory, longer time series, greater spatial coverage and the appropriate mass-conserving salinities and transports give an estimate of only about one-quarter for the reflux coefficient at this site. However it now appears that about two-thirds of the water in Colvos Passage refluxes into East Passage due in part to the local transport maximum in these passages and the clockwise circulation around Vashon Island. The maximum entropy method applied to the septuple junction (including rivers) in the Admiralty Inlet mixing zone requires further refinement before these results can be finalized.

Future plans include the incorporation of dissolved copper as a quasi-conservative tracer and a study of the circulation and refluxing on the seasonal time scale.

# A CHANNEL MODEL OF TIDES AND TIDAL CURRENTS IN PUGET SOUND

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A linear tide model of Puget Sound has been developed at PMEL in which the Sound is represented by a network of 79 one-dimensional channels (Lavelle, Mofjeld, Lempriere-Doggett, Cokelet and Gill, in preparation). Linear dynamics are justified as a first step toward understanding the regional behavior of the tides, a reasonable approach since Puget Sound is a deep estuary and the observed over-tides (e.g., M4) are small. The primary model results are detailed distributions throughout Puget Sound of harmonic constants (amplitudes and phase lags) for the cross sectionally-averaged tides and tidal currents. Also derived from the channel model are estimates of tidal dissipation, drag coefficients and tidal prisms (volume exchange).

The model focuses on the major tidal constituents (O1, P1, K1, N2, M2, S2). For each tidal constituent, the model assumes that the tidal motions in a given channel can be represented by a pair of standing waves at the frequency of the constituent. The waves satisfy an ordinary finite difference equation in the along-channel coordinate where the cross-sectional areas, depths and segment lengths needed in the equation are obtained from the PMEL Bathymetric Data Base (Cokelet, this Workshop). The waves in different channels are coupled through a set of conditions at the junctions between channels and at the ends of the network: continuity of tidal height and transport at the junctions, zero-transport at the closed ends of terminal channels and equality with the observed tidal height at the entrances to Admiralty Inlet and Deception Pass. The amplitudes and phases of the waves are then found by solving a matrix equation obtained from these conditions.

The model tidal heights were tuned to observed distributions of the tidal harmonic constants of the dominant current constituent M2 by adjusting linear drag coefficients within the channels and junction parameters that control the extension of the channels into the junction areas. To get a close fit of the model tides to the observations, it was necessary to assume extraordinarily large drag coefficients (equivalent to $C_d$ values 4-5 times those commonly used) in Admiralty Inlet and The Narrows. Crean (1969) found a similar result for the channels near the San Juan-Gulf Islands in his one-dimensional tide model of the Straits of Juan de Fuca-Georgia. These results suggest that there must be additional dissipation mechanisms at work in or near the high-velocity channels of the region. Possible mechanisms include eddy formulation and wave dispersion along the irregular shorelines, buoyancy work by tidally-generated turbulence in the stratified water column and dissipation of high-velocity jets emanating from the channels.

Good agreement is found between tidal transports (cross sectionally-integrated currents) from the channel model with the few detailed sections that have observed in Puget Sound. The channel model does underestimate the tidal currents in Colvos Passage, probably because it does not contain non-linear processes such as the high-velocity jet that flows northward out of The Narrows during ebb. The channel model estimates the total M2 and K1 dissipation rates in Puget Sound to be 220 and 31.5 MW, respectively. The total M2 tidal prism for the entire Sound is 4.9 $km^3$ and 3.7 $km^3$ for K1.

The model harmonic constants have been incorporated into a prediction program that computes time series of tides and tidal currents. Predicted time series have been used for planning field studies at PMEL and as open boundary conditions for multi-dimensional models of subregions within the Sound (Chu, this Workshop).

# A LATERALLY AVERAGED MODEL OF ADMIRALTY INLET AND THE MAIN BASIN OF PUGET SOUND

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A numerical model capable of describing tidal currents and baroclinic and wind driven circulation in Admiralty Inlet and the main basin of Puget Sound is being developed. The model is a two-dimensional laterally-averaged description because of the long, deep, and narrow character of the system and because a model of reduced dimension permits longer simulations. The model is intended to address the propagation of quasi-fortnightly intrusions of denser oceanic water across the sills in Admiralty Inlet and down the axis of the main basin. It must also describe the substantial variations of tidal currents throughout the Sound and the effects on currents of time-variable winds and river discharge. These are the minimum requirements of a model of the Sound that is intended to be useful in along-axis water quality simulations where tidal-time scale motions are important.

The model we describe is a primitive equation model that conserves mass, momentum, and salinity. The turbulence kinetic energy equation is used in defining the time- and space -dependent coefficients for the diffusive exchange of momentum and salt. An equation of state and turbulence length scales must also be specified. Boundary conditions required for the solution include specification of the sea-surface height and salinity profiles in time at the entrance, and histories of the distributions of wind stress and of river discharge. The model is solved on a rectangular grid by finite difference. Model output consists of current velocity and salinity histories at interior points over the length and depth of the system.

The model differs from many previously developed laterally-averaged models of estuaries in three ways. First, since Puget Sound is geographically complex, the model must be written to accommodate a network of branched channels. Second, the model must encompass a mechanism which permits and restricts the passage of dense water over the sills in Admiralty Inlet. Since the occurrence, strength, and duration of the intrusions appear to be controlled, in part, by the degree of turbulent mixing occurring in Admiralty Inlet, the model must incorporate time-dependent vertical mixing of momentum and salt. This is accomplished through a turbulence closure scheme. Third, the model must adequately represent the propagation of the intrusion down the axis of the main basin once the intrusion begins. Propagation of a density front with relatively large advection speed requires a special numerical scheme to deal with the artificially large numerical diffusion usually attendant with such motion. An estuarine model addressing all these aspects simultaneously has not been previously available.

The present realization of the model treats Puget Sound as nine interconnected sub-basins, each represented as a channel of uniform depth and width and having rectangular cross section. The four sub-basins in the model comprising Admiralty Inlet and the main basin are treated in two dimensions, while the remaining branches (Hood Canal, Whidbey Basin, Colvos Passage, and south Sound) are one dimensional. The model currently resolves motions at a 3 km scale horizontally and a 10 m scale vertically. Use of semi-implicit and time-splitting techniques permit the economical simulation of motions over fortnightly to monthly time scales.

Model results are now becoming available. Within the limits of the geometric and bathymetric definitions presently given the sub-basins, tidal strengths and vertical distributions are adequately described. Gravitationally driven intrusions are seen to propagate down the axis of the main basin with a speed of approximately 20 cm/s. These currents superimpose on the tidal currents at each location. Conditions for the passage of the intrusions across Admiralty Inlet are not yet identified, but it seems clear that their occurrence will be quite sensitive to the parameterization of the mixing and to the discharge of fresh water out of Whidbey Basin.

# COASTAL MODELING NEEDS AND EXPERIENCE OF THE CORPS OF ENGINEERS

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Coastal districts of the U.S. Army Corps of Engineers are among the primary users of end products of model investigations of nearshore oceanographic processes, either directly in the engineering and design of Corps projects, or indirectly in permit evaluations. More often than not, hydrodynamic data are not available for the desired location, and the use of physical or numerical models becomes an important, if not critical element in the design and evaluation process. In addition, models are the only means of assessing the effects of proposed modifications to the local bathymetry. Few, if any, projects can afford the time and expense to collect sufficient field data to fully describe all oceanographic processes throughout the project area. Inevitably, the project evolves so that at least some aspect of the project is no longer described by the original data set. This same problem occurs to a lesser extent with physical models and complex numerical models. Even if, by some stroke of luck, a "complete set of good, usable field data" were available, criticism of the precise location, depth, period of record, or some other detail seems to be inevitable. As a consequence, the use of subjective "professional" judgment in interpreting data and predicting outcomes becomes necessary, but often leads to differing conclusions. An unresolvable impasse between the "proponents and opponents" of the project ensues. The flexibility and "instant replay" capabilities of numerical models, and to some extent physical models, sometimes offer a means of avoiding such dilemmas.

The Seattle District's use of modeling of oceanographic processes has not been extensive, although the need often existed. The most ambitious physical model endeavor was a 10-year long study of the Grays Harbor by the U.S. Army Engineer Waterways Experiment Station (WES). In addition, the University of Washington has conducted several physical model studies for the District to determine tidal circulation and flushing characteristics of marinas. Only recently has the Seattle District utilized the numerical modeling capabilities of WES for a specific project in Puget Sound. This project was the Puget Sound Dredge Disposal Analysis (PSDDA), a 3-year study that was intended to furnish the basis for environmentally effective plans for unconfined (open water) disposal of dredged material in Puget Sound. To assist in establishing the disposal site locations, WES, at the request of the Seattle District, conducted a numerical model investigation of the central portion of Puget Sound to predict areas of high current speed. Limited time and funding constrained the study to a two-dimensional (2D), vertically integrated modeling approach. Only after the model study was well under way was a decision made to locate the disposal sites at nondispersive, low energy areas. As anticipated, the model did not provide detailed information on current speeds in the protected embayments where the disposal sites were placed finally, but the results were used to confirm conclusions regarding general circulation patterns.

The particular 2D model (WIFM) used in the PSDDA studies employed a variable rectilinear grid to determine areas of high currents in the central portion of Puget Sound, where the hydrodynamics is reasonably 2D in character. It was calibrated and verified for two periods in 1981; model results were compared with tidal amplitudes and currents predicted by using harmonic analysis of observed data. There was good agreement. Peak currents at disposal sites were determined for both of these periods as well as for the extreme spring tide event of December 1985.

In general, Corps modeling strategy is to use the best available modeling technology commensurate with the needs, objectives and available resources of Corps projects. Both two- and three-dimensional (3D) models are used depending on the particular situation. Current Corps preference is to use, wherever feasible, coastal hydrodynamic models, which take advantage of boundary-fitted curvilinear horizontal grids, to solve long wave problems since grid lines can be made to follow boundaries, channels, contours, etc. Moreover, depth-adaptive grids can be developed and used with this approach. For 3D models, sigma stretching is used in the vertical. At present, such a 3D model called CELC3D is being used by WES in San Pedro Bay to simulate circulation and transport in Los Angeles-Long Beach Harbors, as a part of the model enhancement program for the harbors. The results of the hydrodynamic model will be used for simulation of water quality in the Bay.

Recently, the Corps and the U.S. Environmental Protection Agency have concluded a Memorandum of Agreement to use CELC3D to study circulation aspects of the Chesapeake Bay and to drive water quality models of the Bay. This decision was made after extensive technical review of available hydrodynamic models. The Chesapeake Bay Study, which is a multi-year project, involves modeling water quality for long-term (order of years). This in turn requires methodology for running the hydrodynamic model for periods of the order of an event, season, or year so that the long-term hydrodynamics of the Bay can be synthesized to drive the water quality model. The details of the modeling strategy are still to be decided, but the prospects are exciting. Similar technology can be applied to Puget Sound also, in view of the complex 3D nature of the hydrodynamic processes in the Sound as a whole.

# VERTICALLY AVERAGED AND THREE-DIMENSIONAL MODELS FOR CENTRAL PUGET SOUND

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In this study, a two-dimensional vertically averaged and a three-dimensional tidal model are implemented for Central Puget Sound from Point Wells to the Narrows at Tacoma. Boundary conditions for both models are cross-sectional M2 and K1 transports calculated from the channel tide model by Mofjeld and Lavelle (see earlier presentation in this workshop). A uniform horizontal staggered grid of 762 m is used for both models. For the three-dimensional model, the Sound is represented by two to five different vertical layers of variable thickness. Limited by the explicit (leap frog) finite difference scheme used, integration time step for the three-dimensional model is six seconds. The long-term stability of the three-dimensional model is ensured by periodic use of a smoothing operator (suggested by P. Killworth, 1984) during time integration. The two-dimensional model is solved by the implicit Leendertse scheme which allows a 16-second integration time step for the same spatial resolution. Both models currently run on a CRAY X/MP-48 supercomputer at the San Diego Supercomputer Center.

To eliminate the effects of arbitrary initial conditions in the solutions, both models need to be spun up for at least four tidal cycles for the tide, and seven cycles for the tidal current. Calculated tides from both models compared favorably with the observation. The comparison between calculated and observed tide and the calculated tidal current ellipses are presented in the workshop. Further verification of the model results are ongoing.

To better characterize the tidal transport within the Sound, particularly the exchanges between the urban bays and the Sound, an Eulerian-Lagrangian transport model will be applied to the study site. The proposed applications of the two- and three-dimensional Eulerian-Lagrangian transport models for Central Puget Sound are presented at the workshop. The potential usefulness of the proposed models for decision making in a variety of engineering and planning problems is discussed.

# MATHEMATICAL MODELING OF THE STRAITS OF GEORGIA AND JUAN DE FUCA

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During 1969 to 1985, Dr. P.B. Crean of the Institute of Ocean Sciences, Department of Fisheries and Oceans, developed a series of computer models for calculating the physical movement of water in the Strait of Georgia - Juan De Fuca Strait and Puget Sound (for convenience, we will refer to this system as the Strait of Georgia). The circulation in this system is due to a combination of forcing factors which include tides, density gradients due to temperature and salinity structure, atmospheric pressure gradients, tangential wind stresses, buoyancy effects associated with fresh water discharge mainly from the Fraser River, and water level gradients associated with disturbances propagating from the Pacific Ocean through the mouths of the Juan De Fuca Strait and the Johnstone Strait.

The following models have been developed (GF stands for Georgia-Fuca).

GFI. Barotropic one-dimensional tidal model
(grid size E = 22.4 km)

GF2. Barotropic two-dimensional tidal model
(grid size = 4 km)

GF3. Barotropic two-dimensional tidal model
(grid size = 2 km)

This model includes only the southern part of the Strait of Georgia and the Juan De Fuca Strait. This model formed the basis for a tidal current atlas published by the Canadian Hydrographic Service.

SAM (Small Area Model): A fine grid (1 km) model for a selected small area.

LAM (Limited Area Model): Similar to SAM, but differs in the input boundary conditions.

GF4: This is also called the upper layer model. This model computes the spreading of the Fraser River plume in the Strait of Georgia, under the influence of tides and winds. (Grid size = 4 km).

The models SAM, LAM and GF4 were developed by Dr. J.A. Stronach of the Pacific Ocean Sciences Ltd., in Vancouver.

GF5: Baroclinic one-dimensional model
(grid size = 22.4 km)

GF6: Three-dimensional model
(horizontal grid size = 4 km, eight layers in the vertical)

GF7: Barotropic fine grid tidal model
(grid size = 2 km)

To avoid any confusion between GF2, GF3 and GF7; model GF2 has a 4 km grid and included the Strait of Georgia, northern channels, Juan De Fuca Strait and Puget Sound. Model GF7 has a grid size of 2 km and thus is more refined than model GF2 (except the one dimensional models for the northern channels were better resolved in GF2). Model GF3 is similar to GF7, except it included only the southern part of the Strait of Georgia and the Juan De Fuca Strait. In addition to the forcing factors for water movement mentioned above, there are at least three other sources. These are wind waves, storm surges and tsunamis. Wind waves are present to some degree almost all the time. Storm surges occur in this system on rare occasions and tsunamis occur much less frequently.

In early 1979 it became obvious that a three-dimensional model is required to provide information on water movement for applications to fisheries, biological and pollution studies and problems dealing with sewage outfalls, mine tailings and construction of coastal structures. At that time Dr. J. Backhaus of the University of Hamburg in the Federal Republic of Germany has developed a three-dimensional model for the German Bight of the North Sea and was interested in testing his model for an entirely different region. Through collaboration between Dr. P.B. Crean and Dr. J. Backhaus, the model GF6 was developed during 1980.

# THE THREE DIMENSIONAL NUMERICAL MODEL OF PUGET SOUND

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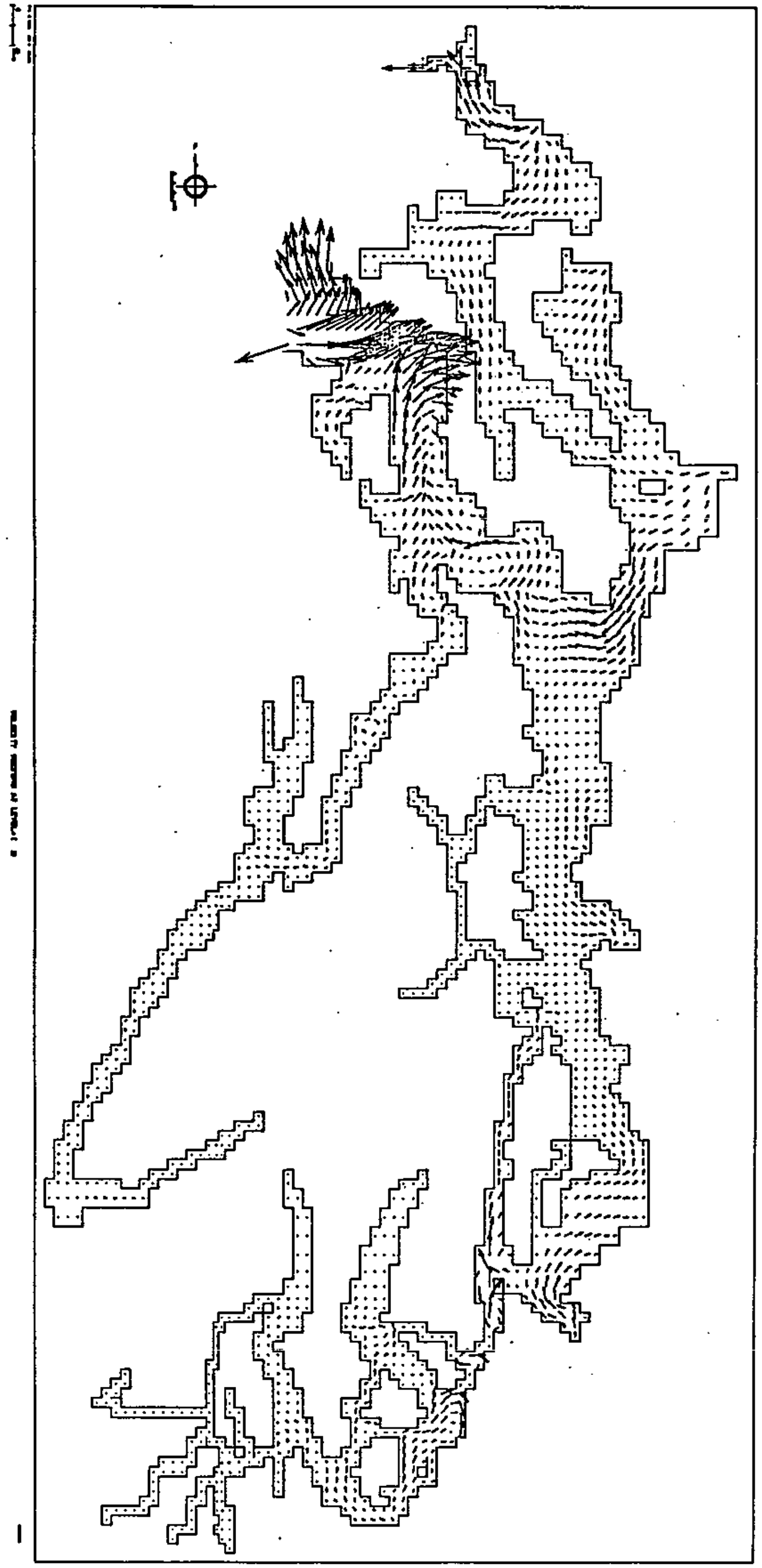
In terms of oceanography, an estuary such as Puget Sound is referred to as the region where the water exchanges with the open ocean through the mouth, and sea water is diluted by the fresh water discharges from land. In most estuaries, concentrations of substances varies both in time and space, affected by the irregular topography as well as by various forces such as tide, river inflow, surface wind, and density gradients, etc. Hydrodynamical processes are, therefore, very complicated. One of the most important factors affecting them is the density gradient from upper to lower bay. Density induced current may become one of the important mechanisms which characterizes the estuarine circulation. The wind induced current and tidal current are also important mechanisms.

The main purpose of this investigation is to give a brief description of circulation in Puget Sound induced by these mechanisms using a numerical model.

For this purpose, the three dimensional model, "multi-leveled" model are applied to Puget Sound. Estuarine circulation is formulated by a set of nonlinear equations of motion, continuity, salt and heat conservation. Numerical experiments of Sound circulation have been carried out using 136*73 variable mesh each 1 km (average) on a side horizontally and irregular 5 levels including the smallest thickness of 5 m. The computation is now going on. The result of the computation for the first level is shown in Figure 1 as an example.

The procedure of this investigation is as follows: reproduce the barotropic tide, gravity induced circulation (incorporate the salt conservation), wind induced circulation. Through this experiment, the appropriate values of various parameters included in model are examined.



# THREE-DIMENSIONAL HYDRODYNAMIC AND TRANSPORT MODELING OF SEQUIM BAY, WASHINGTON

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Mathematical simulation and field studies including dye dispersion and drift float/drogue tests were performed to predict the migration of proposed sewage effluent released at the rate of 0.134 $m^3/s$ (3 million gallons per day) to the Strait of Juan de Fuca just outside of Sequim Bay, Washington. Because of the importance of vertical and lateral flow circulations in relation to the overall flow phenomena in the study area, we applied the time-varying three-dimensional model, TEMPEST, to Sequim Bay and the adjacent area of the strait to predict distributions of flow and sewage effluent as they varied during a mixed semidiurnal tide with one major and one minor tidal cycle.

TEMPEST is a finite difference model that simulates flow, turbulence, heat and mass transfer by solving for the following:

- conservation of mass for fluid (the Continuity Equation)
- conservation of momentum (the Navier-Stokes Equation)
- conservation of turbulent kinetic energy (the K-ε Model)
- conservation of mass for constituents including salinity.

In addition, the Equation of State is used in the model to define the fluid density as a function of temperature and salinity. The model numerically solves hydrodynamics explicitly and transport implicitly.

TEMPEST was used to simulate a complex flow field and sewage effluent concentrations in Sequim Bay and its vicinity in the Strait of Juan de Fuca for a 15-day period. The model accounted for tidally varying velocities across one of two open boundaries and vertical velocities that express the water surface elevation change resulting from tides as boundary conditions. Comparisons of the predicted velocity field for both temporal and spatial variations indicate very good agreements with measured data. Predicted sewage concentrations also agreed well with those obtained from dye concentrations.

The model results revealed that all of the sewage effluent released during flood tides entered Sequim Bay and vertical and lateral flow circulations occurred in the bay at the maximum flood, effectively mixing the effluent within the bay. During the simulated ebb tide, a large circulation formed just outside of the bay trapping the sewage effluent. The effluent was then transported into Sequim Bay during the subsequent flood tide. The model study results also indicated that it would take approximately 10 to 15 days for the effluent concentration to approach final quasi-equilibrium conditions in Sequim Bay (concentrations approximately 2500 to 5000 times lower than the effluent concentration at the outfall). The simulation results indicate that relocating the proposed outfall outside of the circulation formed during ebb tides would significantly reduce any potential environmental impact caused by the proposed sewage outfall.

The model results were animated to create a motion picture showing the tidally varying flow and sewage effluent concentration. The visualization of space and time-varying simulation results through a motion picture is a useful way to enhance modeler's understanding of the complex flow and transport phenomena. It can also be used as an aid to help communicate model results to a layman.