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REPORT OF THE LONG ISLAND SOUND MODELING WORKSHOP
27-28 JANUARY 1986

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I. INTRODUCTION

This report is a summary of the deliberations and conclusions of the participants of a workshop held on the 27th and 28th of January, 1986, dealing with the general subject of hydrodynamic and water quality modeling of Long Island Sound. This workshop was convened jointly by the Marine Sciences Institute, University of Connecticut, and the Marine Sciences Research Center (MSRC), State University of New York, and was held at MSRC in Stony Brook, New York, under funding provided by the U.S. Environmental Protection Agency (EPA).

The workshop resulted from a recommendation made by the Technical Advisory Committee (TAC) to the Management Committee of the EPA Joint Federal - State Agency Long Island Sound Estuarine Study. A proposal to hold the workshop was prepared by TAC and approved for funding by the Management Committee. The proposal listed as the purposes of the workshop the following: (1) to review the state of the art of hydrodynamic and water quality modelling of estuaries; (2) to assess the kinds of modelling efforts which would be most useful in fulfilling the expectations for management of the Long Island Sound system; (3) to prepare a detailed RFP for a modelling initiative; and (4) to recommend an observational program consistent with the proposed modelling initiative selected.

W. Frank Bohlen, Marine Sciences Institute, University of Connecticut, and Donald W. Pritchard, MSRC, were the co-conveners of the workshop. Harry H. Carter, Professor Emeritus, MSRC served as Reporteur. The plan for the workshop was to have, to the extent possible while still maintaining some semblance of order, free discussions among the invited participants, who were, in the words of the proposal, to be a "small group of widely recognized experts in modelling". To set an initial framework for the meeting, a description of the EPA Joint Federal - State Agency Long Island Estuarine Study, and its relationship to the EPA National Estuary Program, was given by Michael S. Connor, Water Management Division, EPA, Boston. This was followed by a brief summary of the existing knowledge of those aspects of Long Island Sound which are pertinent to hydrodynamic and water quality modeling of this water body, given by the two co-conveners. In order to keep the discussion going along lines pertinent to the purposes of the workshop, the co-conveners would from time to time summarize the alternate arguments which had been made up to that point, and would propose consensus conclusions to serve as "straw men" for the purpose of stimulating further output from the participants.

The number of active participants at the workshop was therefore intentionally kept small, in order that the above described format would have the best chance of providing useful results. A list of the invited participants who attended the workshop is attached to this report as an appendix. In addition to the invited, active participants, there were invited observers from the federal, state and regional agencies involved in the EPA Long Island Sound Project. A list of the observers who attended the workshop is also included here as an appendix.

I. THE EPA JOINT FEDERAL - STATE AGENCY LONG ISLAND SOUND ESTUARINE STUDY

The National Estuary Program began in FY 1985. Funding was provided for four estuaries -- three in the NE - Buzzards Bay, Narragansett Bay, and Long Island Sound -- and one, Puget Sound, in the NW. At the time of establishment of the EPA National Estuary Program there was an existing EPA sponsored estuarine study in the Chesapeake Bay, and there were also related EPA sponsored studies in the Great Lakes. The EPA Long Island Sound Estuarine Study (LISES) is thus a part of the National Estuary Program, and the overall goals of the National Program are thus pertinent to the EPA LISES. These goals, as listed by Michael Connor in his presentation to the workshop, follow:

To protect, maintain, and restore environmental quality of estuaries

To develop state/federal/local partnership and consensus

Where appropriate, to use existing CWA regulatory authorities to attain these goals

To develop public awareness of estuarine complexity

To increase understanding of needs and benefits of basin wide planning/management
- **Especially to relate source loadings to resource impacts, with a focus on such impacts**

To develop plans for abatement and control of point/non-point pollutant loadings
- **Specifically, to develop alternate control strategies**

To develop basin-wide management plans for:
- **living resources**
- **water quality**
- **sediment quality**

To develop an acceptance by society of the private/public costs of pollution abatement

To provide for technological transfer to state/local government for implementation of any plan of action developed by the program

To recognize that case studies drive national policy

Each of the specific estuaries within the National Estuary Program has a management structure consistent with EPA's approach for attaining the goals as listed above. A particular problem in the management of a large estuary such as Long Island Sound is the fact that regulation of the various uses of such an environment involves a number of federal, state and local agencies. Responsibilities of such agencies are often overlapping, sometimes to the extent that there are delayed or inadequate responses to adverse impacts made on the environment. A key feature of the EPA approach to attaining its goals of protecting, maintaining and restoring the environmental quality of estuaries is to develop a consensus among the various state and federal agencies and the concerned public groups as to what the problems are, and as to what the goals for the estuary should be. For the most part, the actions indicated by the results of the studies under the EPA LISES will fall under the responsibilities of the state and local governments for implementation. It is anticipated that the costs of clean-up will be large. The purpose of building a broad consensus during the course of the study is to increase the likelihood that the actions indicated by the results of the study will be implemented.

The management structure established for the EPA LISES then includes representation from the broad base of responsible and interested groups. At the top is a Policy Advisory Committee, composed of the Regional Administrators of EPA Region I and Region II, and the Environmental Commissioners of the State of Connecticut and the State of New York. Most of the day to day oversight of the work of the LISES takes place through the Management Committee, which meets approximately monthly and provides direction for the various ongoing studies, and approves new initiatives. Michael Connor of EPA Region I and Jo Brecher of EPA Region II serve as staff for the Management Committee. Representatives of the Department of Environmental Conservation of the State of New York, the Department of Environmental Protection of the State of Connecticut, the Interstate Sanitation Commission, and the National Ocean and Atmosheric Agency serve on the Management Committee, as do the Chairs of the Citizens Advisory Committee and the Technical Advisory Committee.

The Technical Advisory Committee serves as a conduit for the passage of advice to and information from the Management Committee, on the one hand, and the scientific and technical community on the other. Similarly, the Citizens Advisory Committee serves as a conduit for the passage of advice to and information from the Management Committee, on the one hand, and the lay public of the region on the other.

The management structure also includes ad hoc advisory work groups to provide advice on specific technical questions to the Management Committee. At present there are two continuing work groups dealing with areas of particular concern to the LISES, one on toxics and the other on low dissolved oxygen in the western part of the Sound. Two other work groups are also in existence, one dealing with living marine resources and the other with sources of pollution to the Sound. The participants and observers at this workshop could be considered as having constituted a special advisory work group.

The specific goals of the EPA LISES are: (1) pollutant load reduction; (2) water resource management; and (3) protection of living resources. The study is endeavoring to: (a) determine what are the uses of the Sound that society wants protected, what are the living resources in the Sound that are perhaps adversely affected by man's activities, and what are the resources that we want to manage in the Sound; and (b) to tie these findings in with pollutant load reduction, which is the major management tool of EPA.

The major EPA programs affecting estuarine resources -- that is, the mechanisms at the EPA regional level that can be used to encourage and in some cases enforce pollutant source control for environmental protection -- are: (1) construction grants for the building of new treatment plants; (2) point source discharge permits for industrial or municipal waste discharges; (3) enforcement of the conditions of those permits; (4) review of permit applications for and overview of dredging and filling operations; (5) wetlands protection; (6) superfund cleanup; and (7) development of non-point source control programs. At the national level, EPA undertakes in-house research on estuarine processes as well as providing support for extramural research in this area.

It is EPA's present intention that the studies of the four estuaries listed above will cover a period of about five years, at an annual funding level of about $1M per estuary.

The Technical Advisory Committee has developed a prioritized list of problems requiring research efforts, and for several of these TAC has developed a research plan. Two problem areas considered to be of high priority are hypoxia in the Western Long Island Sound, and the distribution and the effect of toxics in Long Island Sound. A group of investigators who met with TAC and with representatives of the Management Committee to consider the research activities which would contribute significantly to knowledge necessary for solution of these problems made a strong recommendation that a group of experts be asked to provide advice on the type of modeling of Long Island Sound which should be undertaken by the EPA LISES. This workshop is the result of that recommendation.

III. AGENCY EXPECTATIONS FOR THE MODELING WORKSHOP

Michael Connor, the EPA Region I coordinator for the LISES, gave the workshop participants a summary of his assessment of what the federal and state agencies expect from this workshop. These expectations must be considered within the constraints imposed by funding. It is evident that the EPA LISES is faced with severe budgetary constraints. In view of the many demands for the roughly $1M per year to be available over the next 4 years (the first year of the five year study has already past), it is not likely that more than a few hundred thousand dollars will be available over the life of the LISES for modeling. By comparison, the EPA Chesapeake Bay program is considering a roughly three year hydrodynamic and water quality modeling effort at an estimated cost of over $2M.

Within this monetary constraint, the state and federal agencies which make up the EPA LISES would like this workshop to advise them as to what could be accomplished by a modeling effort funded at, say $100,000 per year for a period of, say, three years, and what additional accomplishments would result from higher levels of funding.

These agencies suggest that a phased or modular approach to the hydrodynamic and water quality modeling of LIS be undertaken. EPA and the various state and interstate agencies expend funds in the evaluation of individual permit requests, such as request for the waiving of certain discharge requirements, which currently involve the use of small scale models for use around points of discharge in local coastal waterways and harbors. There is a perception that much could be gained if there existed an overall model of the Sound and its tributary tidal waterways which could be broken down into modules for application to local problems, and also used over a large segment of the Sound to determine the interaction of a number of distributed local sources.

The nature of the probable ultimate user group or groups should be a factor in considering the type of models which are to be developed for use in the Sound. It is anticipated that there will be a need to utilize the models developed during the EPA LISES for the evaluation of future changing scenario's of man's interaction with the Sound and its resources, and for reevaluation of the impact of existing waste discharges as the permits for such discharges come up for renewal. The agencies consider the need for water quality modeling tools to be an ongoing process. Waste discharge permits come up for renewal every five years, and the hope is that in five years the agencies will be able to do a better job in determining environmental impact and in setting discharge requirements than at present, and that their ability to perform such assessments will continue to improve. The use of these models for implementing such continuing evaluations will fall within the responsibilities of the state and interstate agencies. The fact that these agencies do not have large modeling staffs needs to be included in the consideration of the character of the models to be developed for the EPA LISES.

An important concern of the agencies with respect to the development of hydrodynamic and water quality models of Long Island Sound is that of timeliness of results. Advice is sought from the participants at this workshop as to how a modeling effort can produce a useful tool and also useful results within the time framework of the EPA LISES.

The agencies also raise a question concerning sufficiency of information. How much knowledge of the Long Island Sound environment, and the interactions of man's activities with this environment, is required to manage the system? To what degree would additional knowledge prescribe significant changes in the decisions made by the agencies?

Several of the representatives of the federal and state agency sponsors of this workshop expressed a view that there are nested scales of interest in the Sound. Using the terms macro, meso, and micro in a different context than that used by physical oceanographers, it was suggested that the nested scales pertinent to the modeling effort for the LISES is a macro scale of the order of 100 km, a meso scale of the order of 10 km, and a micro scale of the order of 1 km. In the macro scale there is an interest in general questions such as the extent of influence from the East River, the Thames River, or the Connecticut River. That is, over how much of the Sound is it necessary to look for effects of wastes discharged into these tributary waterways. The agencies view the requirements at this large scale to be somewhat crude. Most of the activities of the agencies take place at the meso and micro scales in connection with the issuance of discharge permits. The process that most of the agencies go through is a type of waste load allocation process, in which water and sediment criteria for the particular body of water that is to be protected are developed, pollutant sources to the water body are identified, and some sort of source fate and transport modeling is undertaken. The model results are then compared with the water and sediment criteria which had been established for the subject waterway. The model is exercised for various waste loadings to determine the capacity of the system -- that is the maximum waste loading at which the criteria are still satisfied. This waste loading is then allocated among the various sources, a process which usually results in requiring additional treatment of the wastes at the source prior to discharge.

In summary, the agencies have a need for models which they can use to answer practical questions concerning: (1) the establishment of water and sediment quality criteria; (2) waste load allocations within restricted waterways; (3) pollutant specific conditions to be placed on individual discharge permits; (4) the interaction of multiple waste sources within harbors and along adjacent coastal reaches of meso scale dimensions; and (5) the extent of the open Sound, at macro scale dimensions, within which adverse environmental impacts occur as a result of waste discharges into tributary waterways and along the shorelines of the Sound. Modeling for the purely scientific purpose of improving our understanding of the hydrodynamic, biochemical, biological and geochemical processes of importance in the Sound is not a goal of the EPA LISES.

IV. A BRIEF SUMMARY OF EXISTING KNOWLEDGE OF THOSE ASPECTS OF CIRCULATION AND PROPERTY DISTRIBUTION IN LONG ISLAND SOUND WHICH ARE PERTINENT TO HYDRODYNAMIC AND WATER QUALITY MODELING.

The co-conveners of this workshop undertook a review of published and unpublished papers and data sets dealing with the circulation and property distributions in LIS, and presented a summary of this review to the workshop participants. This review showed that while there have been a large number of studies made in the Sound, most cover only local segments of the Sound. Those few studies which were comprehensive in spatial coverage do not provide adequate temporal coverage, and hence information on seasonal and year to year variations is, for the most part, lacking. Most of the published information on tidally averaged circulation comes from the release and recovery of surface and bottom drogues, with results from only a few in situ recording current meter deployments appearing in the published record. There is a good spatial coverage of tide gauge records, and an excellent summary of surface tidal current data is available.

Current meter data from a vertical mooring in the East River near the Western boundary of Long Island Sound was obtained by NOAA during the 1980 New York Harbor circulation survey. However, the only set of in situ recording current meter data showing the lateral and vertical variations in both tidal and residual currents in a cross section within Long Island Sound is described in an unpublished report which was fortunately available to one of us.

Despite the limited published data set, the combination of published and unpublished information makes it possible to reach some very pertinent conclusions about some of the necessary features of any hydrodynamic and water quality models if such models are to successfully serve the EPA LISES.

One conclusion that was immediately evident from this review of existing knowledge was that the LISES would benefit from the preparation of a report which would give a comprehensive analysis of existing published and unpublished data on circulation and property distribution in the Sound, and which also would present a critical review of the conclusions of past studies. Such a properly cited report is not our purpose here. For the immediate purposes of this report on the conclusions and recommendations of this workshop, only a brief summary of our present knowledge of those features of the circulation and distribution of properties in LIS which are pertinent to a determination of the type of hydrodynamic and water quality models required to meet the goals of the EPA LISES will be given. Also, this summary will be given without the normal disclaimers concerning the limited data set upon which they are based, and without a complete listing of the sources of information utilized.

From several standpoints, Long Island Sound is an unique estuarine water body. It is first of all unique in terms of the processes which formed the basin which now constitutes the Sound. Secondly, it is unique in that it communicates with the ocean via passages at both ends. A third unique feature is that the major fresh water sources enter the Sound from the side and not from the upper end.

Measured from Throgs Neck at its western end to Fisher's Island at its eastern end, Long Island Sound is some 150 km long. At its widest cross section just to the east of New Haven, the Sound is slightly over 30 km wide. The Sound is divided along its length into three basins by sills oriented roughly north-south across the Sound. The Central Basin is the largest, occupying over 60% of the surface area of the Sound. The Eastern Basin is second in size, but is the deepest of the three basins. The Western Basin is the smallest in areal extent, and is also the shoalest of the three basins. Several investigators have concluded that Mattituck Sill, which separates the Eastern Basin from the Central Basin, and Hempstead Sill, which separates the Central basin from the Western Basin, significantly influence the circulation in the Sound.

The average annual fresh water flow into the Sound is about 785 m^3/s. The Connecticut River, which enters the Sound only 25 km west of Fisher's Island, contributes some 70%, or 550 m^3/s, of this fresh water inflow. About 10% of the fresh water inflow comes from the Thames River, which enters the Sound less than 10 km northwest of Fisher's Island. Thus over 80% of the Sound lies to the west of the reach within which some 80% of fresh water input enters. The Housatonic River, which enters the Sound just to the east of Bridgeport, or roughly midway along the length of the Sound, also accounts for 10% of the total fresh water input to the Sound. The remaining 10% of the fresh water inflow to the Sound is distributed among all other sources, including the smaller streams along the Connecticut coastline, the even smaller streams which enter the southern shoreline of the Sound from Long Island, and the excess of precipitation directly to the surface of the Sound over evaporation from that surface. There is also a small contribution of fresh water in the estuarine flow from the East River, which will be discussed later in this section.

The distribution of salinity shows a gradient along the longitudinal axis of the Sound, with the lowest salinities at the western end and the highest salinities at the eastern end. The largest longitudinal gradient in salinity is found in the Western Basin. Over a central reach of between one-half and two-thirds of the length of the Sound, the longitudinal salinity profile is relatively flat, with only a very slow increase toward the east. The gradient increases somewhat for a short reach in the eastern end of the Sound. The above description of the longitudinal gradient applies either to the lateral averaged salinity, or to the salinity as measured along the longitudinal axis of the Sound. A longitudinal profile taken along a line parallel to and near to the Connecticut shoreline would not show the smooth pattern described above, but instead would show a series of minimum values as the plumes of low salinity water from the rivers discharging from Connecticut into the Sound are traversed.

The variation in salinity across the Sound is more complex and appears to vary seasonally, although the data set is not adequate to provide a clear picture of such seasonal variations. Two patterns in the lateral distribution of salinity in the Central and Eastern Basins are shown most frequently by the existing data. In both of these patterns the salinity is low on the south, or Long Island side of the Sound, and increases toward the Connecticut side. The two patterns differ in that in one, the transverse salinity profile, that is, the variation in salinity along a line drawn perpendicular to the longitudinal axis of the Sound, shows a maximum at about two-thirds of the distance across the Sound from the Long Island shore. Northward from this maximum, the salinity decreases toward the Connecticut shore. In the second transverse salinity pattern shown by existing data, the salinity maximum offshore from the Connecticut side of the Sound did not appear. Instead the salinity either continued to increase toward the Connecticut shore, or a near zero transverse salinity gradient was found over the northern third of the cross section. It should be noted, however, that these conclusion are based on an interpolation and extrapolation of observations made at a limited number of positions in a few transverse sections, and observations were usually not made close to the Connecticut shore. Thus it is possible, and even probable, that a maximum in the transverse salinity profile existed northward from the observation station closest to the Connecticut shore, and that the salinity actually decreased toward Connecticut in that reach of the cross section, even though these particular data sets did not clearly show this feature.

The low salinity band along the Connecticut shore is consistent with the fact that over 90% of the fresh water inflow to the Sound enters from Connecticut. However, the longitudinal gradient does not seem consistent with the fact that 80% of the fresh water inflow enters the Sound near its eastern end, and half of the remaining flow enters from the Connecticut shore at about midway along the length of the Sound. Nor does the transverse salinity profile, with a maximum nearer to the Connecticut shore than to the Long Island shore, and with the salinity along the Long Island shore sometimes lower than the salinity along the Connecticut shore, appear consistent with the distribution of fresh water inflow.

It appears likely that much of the fresh water discharged from the Connecticut River and the Thames River, particularly during periods of high discharge, moves directly out of the Sound through The Race, and mixes rapidly with the waters of Block Island Sound. Some fraction of the flow from these two rivers, plus the remaining fresh water inflow from the Connecticut shore, moves westward, and these waters are continuously being entrained into the more saline waters which enter the Sound through The Race and flow westward in a tongue-like band parallel to and just north of the central axis of the Sound.

The lowest salinities in the Sound are found at Throgs Neck, at the confluence of the East River with the Sound. The East River is not a river in the strictest sense. It is instead a narrow tidal strait connecting Long Island Sound with the estuary of the Hudson River. The southwestern end of the East River is at the Battery. The tidal range at the east end of the East River at Throgs Neck is much larger than the tidal range at the Battery, and the phasing of the tide at the two ends results in a hydraulically driven flow of tidal period through the East River. Because of the phasing between the tidal rise and fall of the water and the ebb and flood of the currents at Throgs Neck, there is a net residual flow through the East River directed from Throgs Neck towards the Battery; that is, from Long Island Sound towards New York Harbor. The annual average of this net discharge from Long Island Sound through the East River is estimated to be some 340 m^3/s.

The direction of this net flow appears, at first glance, to be inconsistent with the fact the lowest salinities in the Sound occur at its confluence with the East River. Conventional concepts about flow in estuaries is that there is a net flow seaward in the direction of increasing salinity. The net flow from the Sound through the East River represents the net residual flux through the cross section at Throgs Neck caused by the covariance of the harmonic rise and fall of the water surface and the oscillatory ebb and flood of the current at tidal frequencies. Superimposed on this flow there also exists a two-layered estuarine type circulation in the reach of the East River between Hells Gate and Throgs Neck, with the residual flow in the surface layers directed out of the East River into Long Island Sound, and the residual flow in the lower layers directed from the Sound into the East River. The residual flow in the lower layers exceeds the residual flow in the upper layers, and hence the sectional net residual flow is directed from the Sound into East River. Note that since the surface layers in the East River are lower in salinity than the waters in the Sound, the residual flow of these surface waters from the East River to the Sound contributes some fresh water to the Sound. Based on the several existing measurements of the estuarine flow, and of the salinity of these waters, estimates of the fresh water carried with this surface layer flow through Throgs Neck into LIS range from 13 m^3/s to 60 m^3/s. Perhaps coincidently, the mean value of this range of estimates of fresh water inflow to the Sound from the East River is about equal to the approximately 35 m^3/s of fresh water introduced in the sewage discharge to the East River.

Within Long Island Sound, the salinity increases with depth, but the vertical salinity gradient is not as large as in most other large estuaries along the East coast of the US. During the six month period from early spring to early fall, when the temperatures of the Sound waters decrease with depth, the Sound is vertically stratified, though again not to the extent found in most large estuaries. During the remaining half year, when the effect of the vertical variation in temperature on the density is opposite to that due to the vertical variation in salinity, the vertical density stratification in the Sound is either lacking or is very weak.

All evidence indicates that the residual circulation, when viewed in the longitudinal - vertical plane along the central axis of the Sound, exhibits the classical two layered estuarine flow pattern, with eastward directed flow, that is, flow toward Block Island Sound, in the upper layer and westward directed flow, that is flow into the Sound, in the lower layer.

Bottom drogue measurements suggest that the westward directed flow along the bottom is interrupted at the sills which separate the Sound into three basins. Similarly, some investigators have interpreted surface drogue and current meter data to indicate that the westward directed flow along the Connecticut shore and the eastward directed flow along the southern side of the Sound are also interrupted at the boundaries of each of the basins. Thus the surface circulation is thought to be composed of three large counterclockwise rotating eddies. Even if this scenario is correct, there is likely to be some leakage between these eddies, so that some of the water along the Connecticut shore is transported westward from one basin to the next, and likewise some water along the Long Island Shore is transported eastward from one basin to the next.

Data from an unpublished study conducted by R. E. Wilson in 1980-81 are most revealing of the character of the lateral - vertical distribution of the residual (tidally averaged) currents in a cross section extending from just west of Eatons Neck north northeasterly toward Darien, Connecticut. Nine current meters were moored in this section, three each on three taut wire moorings, during four deployments, each of one month duration. Three of these deployments followed one on the other, with only a few hours separating the recovery of the meters from one deployment and the setting of meters for the next deployment. These three deployments were made in the interval from late May to late August, 1980, while the fourth deployment occurred from late December, 1980 through late January, 1981. The upper current meters were located at a depth of 6 m at all three moorings. The mid-depth meters were set at 10.3 m at the south mooring, at 22.4 m at the central mooring, and at 13.9 m at the north mooring, the bottom meters were set at 14.6 m at the south mooring, at 38.8 m at the central mooring, and at 21.7 m at the north mooring.

There was a consistent vertical and lateral structure to the residual current field as revealed by the current meter records from all four of these deployments, though the absolute magnitude of the residual current velocities from individual meters varied by as much as plus or minus 50% of the record length mean values. This pattern shows a residual flow directed down the Sound (eastward) at all depths at the south mooring, a two layered flow pattern at the central mooring, with eastward directed flow at the upper current meter and westward directed flow at the mid-depth and bottom meters, and with westward directed residual flow over most of the water column on the north mooring. The residual flow at the upper meter of the north mooring was close to zero, sometimes directed westward and sometimes eastward. Below this thin near surface layer, the flow at the north mooring increased with depth. This observed pattern suggests that westward directed residual flow occurs in that part of the cross section from just north of the north mooring to the Connecticut shore. This set of measurements suggest that when viewed in the vertical longitudinal plane, the residual circulation shows the caracteristic two-layered gravitational flow pattern found in all other partially mixed estuaries. When viewed in the horizontal plane, however, these observations support the suggestion made by several of the early investigators of the physical hydrography of the Sound that there exists a counterclockwise flowing gyre in the Central Basin, and perhaps in the other two basins as well.

This characteristic pattern shows that the surface of zero residual motion slopes upward from the south side of the Sound toward the north side. This surface is deeper than 14.6 meters at the south mooring and outcrops at the water surface close to the location of the north mooring.

The current meter records from this cross section also show a residual flow of the deeper layers toward the Connecticut shore. This observation is consistent with the findings from bottom drogue studies, which indicate an upwelling along the north shore of the Sound.

The principle axis of the tidal flow showed a departure from a direction parallel to the longitudinal axis of the Sound at all moorings, with the departures at the central and south moorings being particularly large. There was also a change in the orientation of this flow axis with depth.

A clear correlation between the residual currents in the Sound and the local wind velocities has not yet been shown from existing data sets. Meteorological events which take place over the continental shelf south of Long Island and Block Island do result in a filling and emptying of the Sound at periods longer than the semidiurnal tidal period. Since the Sound is in communication with the coastal ocean at both ends, that is, through The Race and Block Island Sound to the east and through the East River, Lower New York Harbor, and the Rockaways - Sandy Hook Transect to the southwest, the relationship between the wind pattern over the adjacent continental shelf and the rise and fall of the tidal mean sea level within the Sound is complex. However, unlike the case in some other large estuaries, meteorological forcing appears not to change the characteristic structure of the residual circulation pattern. From the standpoint of the transport and dispersion of pollutants, meteorological events, both near field and far field, might be considered as providing periods of increase mixing at aperiodic intervals of time.

Even though, as indicated above, we have a fair knowledge of the residual current field, our knowledge of the tidal and tidal current characteristics of the Sound is much better. The primary tidal constituent is the semidiurnal lunar (M2) tide. Long Island Sound is close to being a 1/4 wave length resonator for the M2 tide, with a resonant period of about 10 hours. In this type of system, the tidal range is amplified along the length of the waterway, and the tidal currents are strongest at the entrance (The Race) and weak at the western end. There is a very rapid phase change in the tide in the vicinity of The Race, while over the western 2/3rds of the Sound the phase of the tide shows very little variation. This part of the Sound operates in what is termed the "pumping" mode, and tidal mixing is relatively small under these circumstances.

The corange and cophase lines for the M2 tidal constituent are rotated relative to the perpendicular to the longitudinal axis of the Sound, indicating that the Sound is wide enough for coriolis force to be important, and consequently the tidal wave cannot be a pure standing wave.

Since the tide is a barotropic phenomena, which can essentially be decoupled from motions resulting from density variations and surface wind stress, it is possible to accurately simulate the tide using a vertically averaged two-dimensional hydrodynamic model. Several such tidal models have been applied to Long Island Sound, with the most extensive of such simulations being a model which included Block Island Sound, Rhode Island Sound, Buzzards Bay, and Narragansett Bay. This simulation showed that a critical factor in modeling the tide and tidal currents in Long Island Sound is the accuracy with which the complex bathymetry in the vicinity of The Race is entered into the gridding scheme for the model.

The limited set of observations of the concentrations of phosphate and of the nitrogen nutrients in the East River and in Western Long Island Sound are consistent with the description of the physical circulation in that area given above. The nutrient concentrations in the East River are very high, and there is a gradient of decreasing concentration in an eastward direction through the Western Basin of the Sound. There is certainly a diffusive flux of nutrients from the East River into the Western Basin, associated with the oscillatory tidal motions. However, while the tidal currents in the East River are quite high, they are weak in the Western Basin of the Sound. The extent of the intrusion of high concentrations of nutrients into the Sound suggests that an advective process must be active; in this case the eastward directed estuarine flow of the upper layer of the East River and of the Western Basin.

During the late spring and summer, when vertical density stratification exists, phytoplankton blooms often occur in the Western Basin. Observations of the spatial distribution of dissolved oxygen showed patches of surface waters over the Western Basin which were supersaturated, indicating high primary productivity. At the same time the bottom waters in the Western Basin were hypoxic. While the waters of the eastern portion of the East River are low in oxygen, the lowest dissolved oxygen in the Western Basin during the summer months is not found adjacent to the entrance of the East River to the Sound, but rather on the bottom some 10 km or more into the Western Basin. These conditions have been observed only during the period when the Western Basin is stratified. From early fall to early spring, when there is little or no density stratification, high dissolved oxygen concentrations have been observed at all depths in the Sound. This statement does not preclude the possibility that, even under these latter conditions, there is a thin layer next to the bottom which may have depressed dissolved oxygen concentrations, although no careful studies of such a possible phenomena have yet been reported.

V. WHAT DOES AN ANALYSIS OF EXISTING KNOWLEDGE OF CIRCULATION AND PROPERTY DISTRIBUTIONS IN THE SOUND TELL US ABOUT THE REQUIRED COMPLEXITY OF HYDRODYNAMIC AND WATER QUALITY MODELS OF THE SOUND?

An analysis of the above summary of existing knowledge of the circulation and the distribution of properties in Long Island Sound gives us two messages. One of them is quite clear, while the other is only suggestive.

The clearest message is that Long Island Sound has a spatially complex, three dimensional residual circulation pattern and property distribution pattern. Even though the tidal motions can be considered as essentially two dimensional, the longitudinal and lateral variations in tidal circulation are significant. Of considerable importance in modeling the tidal circulation is the necessity of including a careful simulation of the complex bathymetry in the vicinity of The Race. The only set of data showing the vertical and lateral distribution of currents in a cross section in the Sound shows a highly variable spatial distribution of both tidal and residual currents. This section is located near the western end of the Central Basin. In the absence of contrary information, we must assume that even in the narrower reaches of the Western Basin, lateral and vertical variations in the tidal and residual velocity fields would require a spatially three dimensional simulation to adequately account for the advective flux of pollutants.

The degree of complexity of the temporal variations in the circulation pattern and in the distribution of properties is less clear. There certainly are seasonal variations in the property distributions, and the heat budget of the Western Basin plays a significant role in the seasonal changes in the dissolved oxygen concentrations in the deeper waters of the Western Basin. There are also variations in the magnitude of the residual velocities at a given location which can be as high as plus or minus 50% of the long term mean value, at periods of from 2 to 10 days. However, such meteorologically forced fluctuations do not appear to alter the basic spatial structure of the flow field, and possibly could be considered as contributing to an increase in mixing. Strong storm events over the Sound do produce vertical mixing and sediment resuspension to 20 m or so, and it may be necessary to include some means of dealing with such aperiodic mixing events in any water quality model. However, there is a question as to whether it is necessary that the hydrodynamic and water quality models suitable for use in helping to answer the waste and resource management questions posed by the EPA LISES need to be fully transient state models, driven by real time variations in the boundary forcing parameters.

VI. QUESTIONS TO BE ANSWERED BY THE WORKSHOP

The contents of this section might be considered to have been already provided earlier in this report in the form of the statement of the goals of the workshop as contained in the proposal prepared by the Technical Advisory Committee plus the description of the expectations of the agencies which make up the EPA Joint Federal - State Agency Long Island Sound Estuarine Study. However, the reality of what the Workshop participants felt were attainable tasks, within the constraints of the available time, differs somewhat from the hopes of the planners and the expectations of the sponsors. Also, we would phrase the questions to be answered in a somewhat different way than is the case of either the planners or the sponsors of the workshop. It is prudent therefore to state the questions which were dealt with by the Workshop.

Question 1: Is a hydrodynamic model necessary to provide the velocity field input to the water quality model, or would it be adequate to use a kinematic approach in which the principles of volume and salt conservation are used to deduce an "effective" flow field which accounts for the distribution of salinity, and by inference, would account for the advective fluxes of introduced pollutants?

Question 2: How spatially complex should the hydrodynamic and water quality models be; that is, should the models be fully three-dimensional, or two-dimensional vertically averaged, or two-dimensional laterally averaged, or even one-dimensional sectionally averaged? Could models with different degrees of spatial complexity be applied to different segments of the Sound and its tributary tidal waterways?

Question 3: How complex should the models be with respect to time variability? That is, should the models be steady state models or transient state models? If transient state, should the models be fully time dependent in terms of real time input of varying boundary conditions, or be driven by boundary conditions which vary in time only at tidal frequencies?

Question 4: What is the areal extent required of the models?

Question 5: What is the likely cost of the required modeling effort?

Question 6: What is the probable time frame required to develop models which can produce useful results for the EPA LISES?

Question 7. What field program is required to obtain data necessary for adjustment and verification of the models, and to obtain data for driving the models at the boundaries?

VII. ALTERNATE MODELING STRATEGIES -- ADVANTAGES AND DISADVANTAGES OF VARIOUS APPROACHES TO MODELING OF LONG ISLAND SOUND

A. A Purely Kinematic Modeling Approach -- Is an Hydrodynamic Model of Long Island Sound Necessary?

The simplest approach to the modeling of Long Island Sound considered by the participants at this workshop involves the use of a kinematic modeling strategy, in which the equation of continuity and the salt balance equation are utilized to obtain values of the volume flux and of diffusion coefficients which satisfy the observed distribution of a conservative property, usually of salinity. These values of volume flux and of diffusion coefficients are then used to compute the advective and diffusive terms in a water quality model. This strategy does not involve the use of an hydrodynamic model to provide such inputs to the water quality model.

It should first be noted that this approach is "simple" only in comparison to a coupled hydrodynamic - water quality modeling effort. This type of water quality modeling may involve one, two or three spatial dimensions depending on the complexity of the waterway being modeled and the goals of the modeling effort. For the purpose of describing this modeling strategy, we will consider a model which includes parameter variations in all three spatial dimensions in an elongated tidal waterway, that is, in a waterway in which the length along the longitudinal axis is greater than the width, or lateral dimension, and in which the predominant component of the tidal currents is directed along the longitudinal axis of the waterway.

The following outlines the usual procedures used in the application of this modeling strategy to water quality problems in such a water body.

(1) In this type of water quality modeling the waterway of interest is subdivided into a series of cells, or elements, in the horizontal, with a greater number of cells in the longitudinal than in the lateral directions. Each cell or element is then subdivided into several layers. The cells are usually roughly rectangular in shape, though the solution methods most often used do not require that the opposite sides of the cells be parallel or of the same length. Often the longitudinal dimensions of the cells are set greater than the lateral dimensions.

(2) Observed salinity data is used to obtain an estimate of the mean salinity in each layer of each cell. Either steady state conditions are assumed or a time rate of change of the salt content of each layer in each cell must be determined, based on observations of the variation in the spatial distribution of salinity with time. Usually the equations and the data are considered to be tidally averaged.

(3) For each subelement a volume balance equation and a salt balance equation can be written. In the case of the volume balance, the time rate of change of the volume of the subelement is set equal to the net volume flux through the four sides and through the top and bottom of the subelement. In the case of the salt balance, the time rate of change of the mass of salt in the subelement is set equal to the net advective and diffusive flux of salt through the four sides and through the top and bottom of the subelement.

(4) Since the dimensions of the elements are fixed, the volume of each subelement is constant except for the subelements at the water surface. Hence for all interior elements the volume balance states simply that the algebraic sum of the net volume fluxes through the faces of the subelement must be equal to zero. Since in this type of modeling, the equations are usually taken as time averaged over the tide, and often over longer periods of time, the

variations in the volume of the surface subelements with time is also usually set equal to zero.

(5) In the differential equation expressing the salt balance for an infinitesimal fluid parcel, the diffusive salt flux across a given face of the parcel, per unit area of the face, is expressed as the product of a diffusion coefficient and the gradient of the salt concentration normal to the face. In most kinematic numerical models, the diffusive salt flux across a given face of a finite sized subelement is expressed by the product of an exchange coefficient, having the dimensions of volume flux, and the difference between the salt concentration in the two subelements adjacent to that particular face.

(6) The advective flux of salt through any face of the subelement is assumed to be equal to the product of the volume flux through that face and the mean salt concentration over the area of the face. Thus the equations expressing volume balance have common parameters (the values of volume flux) with the equations expressing the salt balance, for a given subelement.

(7) The volume flux out of (or into) one subelement through a given face is equal to the volume flux into (or out of) the adjacent subelement having that particular face in common. Similarly, the diffusive flux of salt into (or out of) one subelement through a given face is equal to the diffusive flux of salt out of (or into) the adjacent subelement through that given face. Hence both the equation expressing the volume balance and the equation expressing the salt balance for a given subelement will have some volume flux terms and exchange coefficients in common with those in adjacent subelements.

(8) Thus, from the last two items above, it is evident that the equations expressing the volume balance and the salt balance for all the subelements comprise a set of linear simultaneous equations. The number of equations in this equation set is equal to twice the number of subelements. Given the observed salinity distribution in space and time, from which values of the time rate of change of the salt content of each subelement, the mean salinity in the subelement, and the mean salinity at each of the six faces of the subelement, can be determined, then the unknowns are the values of the volume flux through the faces of the elements, and the values of the exchange coefficients. Ideally, one would like to invert the matrix formed from this set of simultaneous equations and solve for the unknown flows and exchange coefficients.

(9) Unfortunately, there are considerably more unknowns than there are equations. Only in the simple one-dimensional case are the volume flux terms and the exchange coefficients uniquely determined by the equation set. For more complex and hence more realistic cases the number of unknowns must be reduced to match the number of equations by: (a) assuming that certain of the advective and diffusive flux terms are negligible; and/or (b) making independent estimates of exchange coefficients (or of diffusion coefficients) through the use of empirical or theoretical relationships which have been developed or verified using independent data sets. For example, for a simulation which is one element wide and two layers deep, that is, for a laterally averaged two layered model, a unique solution for values of the longitudinal and vertical flows and the vertical exchange coefficient is obtained if longitudinal diffusion is neglected.

(10) Assuming that the combination of (a) reduction in the complexity of the continuity equations through neglect of one or more of the advective or diffusive terms, and (b) independent estimation of values of the exchange coefficients, results in a match between the number of unknowns and the number of equations, a solution can be obtained for values of volume flux through each face of each subelement, and of the exchange coefficients not independently estimated. The set of values of the volume flux and of the exchange coeffi-

cients thus determined are the values required, under the assumptions described above, to account for the observed salinity distribution.

(11) These values of the volume flux and exchange coefficients are then used in the advective and diffusive terms in the water quality model.

There are variations, for the most part minor in concept, to the approach described above for the kinematic modeling strategy. Particularly in restricted waterways, other conservative tracers than salinity, such as an introduced fluorescent dye, have been used in the determination of the flow field and of values of the diffusion coefficients. Also, for the prediction of near field pollutant concentrations from a single source, plume entrainment models, similar to smoke stack models used for atmospheric pollution problems, are often employed. A basic problem with the near field "mixing zone" models is that in many situations the assumptions made with regard to the background concentrations of the pollutant in the "dilution" water for the outfall plume significantly affect the dimensions of the part of the plume having concentrations exceeding some predefined criteria. This background level should properly be determined by a model which treats a larger segment of the waterway, and which also includes the interaction between the restricted waterway and adjacent waterways or segments of adjacent waterways.

The consensus view of the workshop participants was that the confidence which could be placed on the results produced using this purely kinematic strategy to water quality modeling of the Sound would not be sufficiently high to warrant the use of such results by the EPA LISES in making management decisions. The major reason for this opinion is that, as described in an earlier section of this report, LIS shows a complex three-dimensional variation in the distribution of flow and of properties. The number of simplifying assumptions which must be made to obtain estimates of the three-dimensional flow field, and of the distribution of diffusion coefficients, using a purely kinematic modeling strategy, removes the process so far from our basic understanding of the physics of motion and mixing that, in the opinion of the majority of the participants in this workshop, a more scientifically Sound approach should be used.

The reason that this kinematic approach to modeling has been described in as much detail as given above, even though the workshop participants consider this approach to be an unsatisfactory method for use by the EPA LISES, is that the existing models that are used by management agencies, or that have been used by consulting firms in earlier studies for the management agencies which are part of the EPA LISES, are for the most part based on the kinematic modeling approach. It is therefore natural that these agencies would look first towards that approach in extending the modeling effort beyond the restricted waterways in which these models have been used to date.

The modeling strategy of choice then involves the use of a hydrodynamic model to obtain values of velocity and at least a first order estimate of values of the diffusion coefficients, to be used to compute the advective and diffusive flux terms in a water quality model. Within this broad framework, there are still a number of possible alternate strategies with respect to the degree of spatial and temporal complexity which should be included in the models.

B. Alternate Modeling Strategies With Respect to Temporal Complexity

Now consider the deliberations of the workshop participants in regard to the question of whether the coupled hydrodynamic and water quality models should be real time models or time averaged models, where the period of averaging is the tidal period, or possibly even longer time periods. During the course of discussion of this question, the following possible approaches were considered:

(1) Fully transient state hydrodynamic and water quality models which would include real time variations in the forcing parameters at the boundaries at both tidal and meteorological time scales.

(2) A fully transient state hydrodynamic model which would include simulation of real time variations in the forcing parameters at the boundaries at both tidal and meteorological time scales. The values of velocity and of the diffusion coefficients output from this model would be filtered to remove the tidal variations, and the values of the residual velocity and the tidal averaged diffusion coefficients input to a tidally averaged water quality model. In this alternate time variations at time periods longer than tidal, i.e. , at meteorological time scales, would be retained in the water quality model.

(3) An alternate similar to (2) above, but in which the out-put of the fully transient state hydrodynamic model would be averaged over time periods of from several days to several weeks, to be used as input to an water quality model averaged over the same time period. The water quality model would retain smoothed real time variations in the advective and diffusive input terms, and in the parameters which control the nonconservative processes affecting the several water quality variables.

(4) A time varying hydrodynamic model at tidal frequencies, but otherwise with seasonally averaged boundary forcing parameters. This model would be exercised in the transient state mode until "pseudo" steady state output was reached, that is, until the variations in water surface elevations and in current velocities output from the model were repeated on successive tidal cycles. The values of velocity and of the diffusion coefficients from the hydrodynamic model would be averaged over the tidal cycle to provide a spatially varying but time independent input for the water quality model. The latter model would be used to solve for the steady state spatial distributions of the water quality variables.

(5) A tidally averaged hydrodynamic model would be exercised to provide input of values of the velocity and of the diffusion coefficients into a tidally averaged water quality model. There are several possible variations of this modeling strategy. The hydrodynamic model could be transient state with respect to time variations in the forcing terms at time scales greater than tidal; that is, at meteorological forcing frequencies, or could be averaged over all time scales. If the hydrodynamic model were to be transient state with respect to meteorological time scales, then the water quality model could be either time dependent with respect to these same time scales, or could be a steady state model. In the latter case, the output of the hydrodynamic model would be averaged over the longest period of the meteorological variations, to serve as a time independent input to the water quality model.

The hydrodynamic modelers at the workshop were of the strong opinion that the hydrodynamic model should be transient state at tidal frequencies. There was not a clear agreement as to whether or not this model should be a real time model with respect to meteorological forcing. There was a consensus, however, that characteristic seasonal scenarios of the variations in the forcing parameters should be established for the seasons of concern, and the hydrodynamic model exercised using such time variations in the forcing parameters to drive the model.

The participants who were primarily water quality modelers, or who had experience in both hydrodynamic and water quality modeling, believed that the water quality model should be tidally averaged, and should use as input the velocity and diffusion coefficient output from the hydrographic model which had been averaged over the tidal period. Several participants expressed a strong opinion that the input data for the water quality model could be averaged over periods of from several days to several weeks, depending on the particular water quality question being asked.

Some readers of this report might at this point question why the hydrodynamic model should be transient state at tidal time scales, only to have the output of the model time averaged over the tidal period to be used as input to the water quality model. Studies of the dynamics of motion in tidal waterways made over the last decade have demonstrated that there is often a significant nonlinear interaction of the components of the oscillatory tidal currents and the residual, or tidal averaged currents, and also a nonlinear interaction of the tidal currents with the bathymetry of the tidal waterway. Both of these processes produce residual current fields. Thus, the residual current pattern determined by tidally averaging the output of a transient state model is not the same as the residual current pattern output from a tidally averaged hydrodynamic model.

C. Alternate Modeling Stategies With Respect to Spatial Complexity

The next question to be addressed concerns the degree of spatial complexity that the models should have. It should first be stated that unlike the question of temporal complexity, the water quality model should have the same spatial complexity as the hydrodynamic model. The alternates with respect to the spatial complexity are: (a) one-dimensional, sectionally averaged, models; (b) two-dimensional, vertically averaged models; (c) two-dimensional, laterally averaged models; and (d) fully three dimensional models.

Each of these modeling strategies could satisfactorily simulate the important features of some part of the Long Island Sound - tributary waterway estuarine system. Anticipating certain conclusions that will be discussed below concerning the required spatial extent of the two models, one-dimensional models would be adequate for the simulation of the East River between Hell Gate and the Battery, while laterally averaged two-dimensional models would be adequate (and required) for the simulation of the hydrodynamic and water quality characteristics of the East River between Hell Gate and Throgs Neck. Vertically averaged two-dimensional models may be adequate for use in some of the tributary bays and harbors along the Connecticut and Long Island shores of Long Island Sound.

However, the longitudinal, lateral and vertical variations of the tidal and residual currents and of the distribution of properties in Long Island

Sound itself, as described above in Section V, require that a three-dimensional modeling strategy be used for both hydrodynamic and water quality models of the Sound.

D. What Should be the Spatial Extent of the Hydrodynamic and Water Quality Model of Long Island Sound

Long Island Sound communicates with the ocean at both the eastern and western ends, and hence the hydrodynamic model should be tidally forced from both ends. At the western end, the segment of the East River east of Hell Gate is a primary source of sewage wastes to the Sound, and hence this reach must be included in both the hydrodynamic and water quality model. However, for a number of reasons Hell Gate is not a suitable western boundary of a tidal model of Long Island Sound, including the fact that there are large spatial variations in the water surface level in a short reach of the East River in the vicinity of Hell Gate. An appropriate western boundary for the hydraulic model is the Battery, at the western terminus of the East River, where there is a permanent tide gauge station. The western boundary of the water quality model should also be located away from the vicinity of the waste discharges into the East River east of Hell Gate. An examination of the variation in the concentration of phosphate along the length of the East River suggests that the Battery would also be a suitable western boundary for the water quality model.

The primary water quality questions posed by the federal and state agency representatives at the workshop involved phenomena occurring in the Western Basin of the Sound. Experience has shown that water quality models should extend somewhat beyond the areas of concern, and there was general agreement that the eastern boundary of the water quality model should be located along a transect across the Sound in the vicinity of Eatons Neck. However, it should be noted that several agency representatives at the workshop also stated that a model of Long Island Sound should be capable of being coupled to models of the tributary estuaries and harbors along the shores of Connecticut and Long Island, so that the extent of the interaction of wastes from the multiple tributary waterways as well as sources located directly on the shores of the Sound could be evaluated. Since a number of important tributary waterways, having significant waste sources, are located to the east of the Eatons Neck transect, consideration should be given to ultimately extending the water quality model eastward to include the entire Sound.

The hydraulic model must provide velocity data throughout the region of the Sound and its tributary waterways which are included in the water quality model. The boundary conditions for the hydrodynamic model require that the time variations of the water surface elevation and of salinity be input at each grid point across the seaward boundary. Providing such data across the Eaton's Neck transect would require an observational program which would involve much greater costs than would extending the hydrodynamic model further eastward. More importantly, the seaward boundary of the hydraulic model should be at the location which can be considered to be the source of the tidal and meteorological driving of the waterway. This indicates that the eastern boundary must be at least at the The Race. Trying to model the hydrodynamic response of Western Long Island Sound to tidal and meteorological forcing using the Eatons Neck transect as an eastern boundary could be compared to trying to model the response of the upper half of a 50 story building to earthquake motions using the twenty fifth floor as the lower boundary, instead of using the ground where the driving forces for the building motion would originate.

As already noted above in Section V, simulation of the response of Long Island Sound to tidal forcing may require that the hydrodynamic model be extended to include Block Island Sound. At least two factors make the transect running from Orient Point to Plum Island, then to Fisher's Island, and then northward to the Connecticut shore, a very unsatisfactory modeling boundary. These factors are the very large slopes to the water surface and the very large spatial variations in the bathymetry in the vicinity of The Race. A suitable boundary for the tidal forcing of Long Island Sound would be a line extending from Montauk Point to Block Island, and continuing from Block Island to Pt Judith.

VIII. OTHER PERTINENT FEATURES OF THE RECOMMENDED MODELING STRATEGY

It was not possible to develop a detailed description of all of the features of the models which should be utilized for the EPA LISES during the workshop, but certain important features of the recommended modeling strategy which were discussed by the workshop participants and which have not yet been described in this report, are listed below.

In its ultimate form, the hydrodynamic model would include a coupled salinity submodel, and the salinity would be computed at all grid points as a function of time, though probably at longer time steps than is required for the hydrodynamic computations. The computed salinity values would be combined with temperature values in an equation of state to compute the spatial distribution of density, which would then be fed back into the model to update the internal pressure gradient term. The values of temperature used in the equation of state would be input to the model in tabular form, and would represent characteristic distributions for the season over which the model was being exercised. Time varying values of the salinity at ocean boundary grid points would have to be input to the model.

Comparison of the computed distribution of salinity with observed values of salinity would provide a verification of the ability of the hydrodynamic model to produce a velocity field which was consistent with a conservative water quality variable.

The hydrodynamic model should also have a second order turbulence closure model for the determination of the vertical viscosities. This closure model would also provide for the computation of values of the vertical diffusion coefficients, to be used in the salinity submodel, and ultimately in the water quality model.

It was generally agreed that initial useful results could be obtained by exercising the hydrodynamic model in a diagnostic mode, in which a salinity and a temperature field, characteristic of the average observed conditions during a season of interest with respect to the water quality problems, would be input to the equation of state subroutine of the model. The steady state residual velocity field would then be computed for use as input to the water quality model.

In its ultimate form, the water quality model must have a sediment submodel, which would provide for the calculation of the sediment oxygen demand and for the exchange of organic materials, of nutrients, and of toxic materials between the sediment and the water column. Initially, a relatively simple simulation of the sediment - water column interaction would be implemented. One possibility would be to input the estimated values of the sediment oxygen demand as a bottom boundary condition, without attempting to have the model compute any of the bottom - water column interactions.

IX. DATA COLLECTION REQUIRED FOR THE MODELING EFFORT

A. General

Observations of various physical, chemical and biological parameters are required at the open boundaries of the modeled region for purposes of running the hydrodynamic and water quality models, and at a number of interior points for the purpose of adjustment and verification of these models. This section will include: (a) a listing of the types of data required for the modeling effort envisioned by the workshop participants; (b) comments on which of these data types appear to already have an adequate observational base, which ones will clearly require an extensive observational program, and which types of data will require some type of observational effort, the magnitude of which can only be determined after the completion of an analysis of all published and unpublished data sets; and (c) a description of the type of observational program recommended by the workshop participants.

With respect to item (c) just above, it should be pointed out that a combination of delays in the arrival of some participants at the start of the workshop (due to bad weather), and the necessity for some participants to depart earlier than the scheduled end of the workshop, resulted in less time being available for this subject than had been planned. As a result it is not possible to report consensus regarding several features of this matter of data collection required for the proposed modeling effort. Instead, for those several features, only individual comments made by the participants, some of them representing conflicting views, will be given.

Several general features of a data collection program related to a modeling effort were raised by the participants. First, one participant strongly recommended that any observational program undertaken for the purposes of providing the data needed for a modeling effort in Long Island Sound be capable of standing on its own, and not be limited by the currently perceived needs of the modeling activity. Another participant pointed out, however, that the severe budget constraints precluded such a stand alone observational program.

There was general agreement that, unless the waterway was very nearly homogeneous in the velocity and property distribution along the dimension of averaging, and was also nonvariant in time, a transient state three-dimensional model would require less data for adjustment and verification than a steady state one- or two-dimensional model.

The basis of this statement can best be shown by use of an example. Consider a tidal estuary in which the physical and water quality parameters vary both in space and time along the vertical and lateral directions, as well as along the longitudinal axis of the waterway. Assume that for the particular problems of concern only seasonally averaged vertical mean values of the flow field and of the distribution of water quality variables are deemed necessary, and hence steady state, two-dimensional vertically averaged, hydrodynamic and water quality models should suffice. If the waterway were actually time independent and vertically homogeneous, adjustment and verification of these models could be based on a single data set taken at a single depth, at a number of horizontal locations. Since the pertinent physical and water quality variables in the waterway in this example vary in time and in the vertical, a sufficient time series of observations must be taken at a sufficient number of depths at each station to obtain time average vertical mean values of these variables for purposes of adjustment and verification of the models.

If, on the other hand this hypothetical waterway were simulated using transient state, three-dimensional models, the frequency of sampling in time and the number of depths at which measurements need be taken could be considerably less than for the case of the two-dimensional steady state model. It would be necessary to obtain measurements several times during the season of concern, at several depths at a number of stations in the horizontal, but not at the frequency and at the number of depths necessary to obtain good estimates of the time average, vertical mean values of the several pertinent parameters. In fact, synoptic data is not required. Verification of the models could be accomplished by exercising them with real time boundary forcing, over the time interval covering the observational program. The observations taken at a given time and location would then be compared to the output of the models at the corresponding simulated time and location. If the sampling program provided sufficient observations in time to show the major seasonal trends, and sufficient measurements in the vertical to reveal the general character of the vertical variations in the pertinent parameters, then if the values of these variables computed by the model "on the fly", so to speak, closely matched the observed, the model could be considered to be well verified.

B. Data Required for Model Calibration and Verification

The data requirements for calibration and verification of the hydrodynamic and water quality models are significantly different, the former requiring measurements of physical parameters while the water quality model requires, for the most part, chemical, biochemical, and biological data. Consequently, the data requirements for the two types of models are discussed separately, even though both data sets may be collected concurrently. The participants spent more time in discussing the data collection requirements for the hydrodynamic model than for the water quality model. However, the group did not agree on the details of station locations for the data collection effort even for the hydrodynamic model, although agreement was reached as to the frequency of sampling, and as to the general character of the required spatial distribution of sampling stations.

(1) For the Hydrodynamic Model.

(a) Time series measurements of salinity, temperature, water surface elevation, and the horizontal components of the water velocity should be made at several depths, at each of several stations located in each of about five cross sections in Long Island Sound. The cross sections should be distributed along the length of the Sound, but spaced closer together in the Western Basin. The number of stations in a given cross section would depend upon the width of the section, with at least three stations in the narrower sections and as many as five stations in the wide sections of the Central Basin. The number of depths at a particular station at which the measurements would be made would depend on the depth of that station. Two depths would suffice at the shallow, side stations with as many as four sampling depths being required for the deep, central stations. Measurements of current speed and direction, of temperature, and of salinity (actually, electrical conductivity, which together with the temperature would give the salinity), would be made using <u>in situ</u> recording current meters having temperature and conductivity sensors. Measurements of the water surface elevation should be made near each end of the cross section using tide gauges, and at the central station in the cross section using pressure gauges deployed at the bottom of the current meter mooring. The sampling interval should be no longer than about 10 minutes, and the duration of a deployment on a given cross section should be at least two weeks. Two such deployments should be made on each cross section during the year of field study. However, these deployments do not have to be made concurrently at all sections. In fact, the sections could be occupied one after the other, and thus the data from two deployments at each of five sections could be obtained in a 10 month period, if the length of the deployments were kept to 14 days each.

(b) Areal distributions of the vertical variation in temperature and salinity should be obtained in the Sound at monthly intervals, over a one year period. Such a data set could be provided from semisynoptic cruises made along the length of the Sound, using a zigzag course to give both lateral and longitudinal information. Stations would be located at intervals along the cruise path, where measurements of temperature and salinity would be made as a function of depth. Continuous recordings of the surface temperature and salinity could be made while the survey vessel was underway between stations.

(c) At least two reference stations should be located in the Sound, at each of which a vertical mooring containing <u>in situ</u> recording currenent meter - salinometer instruments at perhaps three depths. These reference stations should be maintained over the course of a full year, which would require recovery and redeployment of the meters at about monthly intervals.

(d) There was general agreement that an attempt should be made to obtain a continuous time series of measurements of the volume flux through Throgs Neck at the eastern end of the East River. Because of the strong currents and the large amount of ship traffic in this relative narrow waterway, maintaining a vertical mooring of current meters would be very difficult, and it was suggested that perhaps GEK measurements could be made using existing communication cables across the East River.

(2) <u>For the Water Quality Model</u>

Time constraints limited the development of consensus recommendations regarding the required data collection for the water quality modeling effort. In general, it was recognized that observations should be made of the spatial distribution of dissolved oxygen; all forms of phosphorus and nitrogen, i.e., dissolved and particulate, organic and inorganic; particulate and dissolved carbon; and chlorophyll concentrations. Measurements should be made at frequent enough intervals so that the seasonal pattern is revealed. Also, sampling should be more spatially intense in the Western Basin.

The participants at the workshop recommended that this type of water column sampling for the water quality model could be combined with the semisynoptic monthly temperature - salinity cruises recommended above in support of the hydrodynamic modeling effort.

It was also suggested that measurements of the above listed water quality variables should be made at weekly intervals at the two or three reference stations at which continuous measurements of temperature, salinity and current velocity would be obtained over the year of field studies.

Measurements of the sediment oxygen demand and of the exchange of nutrients across the sediment-water boundary would also be required for water quality modeling.

In view of the limited time spent on this subject during this workshop, it is recommended that a special working group consider in detail the required program of data collection for the water quality modeling effort.

C. Data Required for Boundary Conditions During Calibration, Verification, and Production Runs of the Models

Again, the data required for boundary conditions during production runs of the two models are sufficiently different so that the requirements for each model will be discussed separately.

(1) For the Hydrodynamic Model.

There are four types of data needed to drive the hydrodynamic model at its boundaries. These are:

(a) A time series record of the water surface elevation at each grid point across the open ocean boundaries to the Sound.

As proposed earlier in this report, the western boundary of the model would be at the section across the East River adjacent to the Battery, where there is a permanent USC&GS tide gauge station. The narrow width of the East River precludes the need to be concerned about variations in the water surface elevation across this western boundary. The workshop participants also proposed that the eastern open ocean boundary for the hydrodynamic model be along a line from Montauk Point to Block Island, and then to Point Judith. Values of the amplitude and phase of the significant tidal constituents at these three locations are known. The longer period meteorological forced variations in tidal mean sea level are highly coherent in space over distances comparable to the distances between Montauk Point and Block Island, and between Block Island and Point Judith. There are permanent NOAA tide gauge stations located sufficiently near to Montauk Point and to Point Judith so that the real time tidal averaged fluctuations in the water surface elevation along this boundary could be estimated with reasonable accuracy. The combination of these estimates with the computations of the tidal variations in water surface elevation based on the known amplitudes and phases of the principle tidal constituents at Montauk Point, Block Island, and Point Judith could be used to provide real time variations in the water surface elevations along this open boundary, for any selected time interval. However, the elevation of mean sea level relative to a level datum at these three locations is not known, and it may be necessary to adjust the tidal mean water surface elevation along this eastern open boundary in order to obtain adequate calibration runs of the model.

(b) Values of the salinity in each layer, at each grid point along the open boundaries, must be input to the model over the period of any calibration, verification or production runs of the hydrographic model.

In order to use the hydrodynamic model to provide the required representative spatial and temporal distributions of velocity and diffusivity, to be input to the water quality model, it should not be necessary to undertake the collection of a continuous series of measurements along these boundaries. The time variations in the salinity at the open boundary along the line from Montauk Point to Block Island and thence to Point Judith should be relatively small, and the spatial variations along this boundary should be fairly smooth. An analysis of the existing salinity data in the vicinity of this boundary will be required to determine if these data are adequate for the purposes of the modeling effort as described here. In any case, it is likely that only a modest observational program to obtain additional salinity data along the eastern open boundary of the proposed model would be required.

The Battery may be a more critical location from the standpoint of a requirement for open boundary salinity values. Salinity observations at this location, as well as at two or three other locations in the East River, should be obtained during each of the proposed monthly semisynoptic surveys recommended above. The combination of these data with the existing set of salinity observations for the Hudson River and East River in the vicinity of the Battery, including data obtained from the USACE hydraulic model at the Waterways Experimental Station, Vicksburg, Mississippi, should be adequate for the model effort proposed here.

(c) Time histories of the inflows of fresh water is required for the major sources of such flows to the Sound

Daily records of flow at gauging stations on the major rivers entering the Sound are available from the USGS and from various state agencies having the responsibility for collection of such data. Although these gauging stations do not provide flow data for all of the drainage area of these rivers, there is adequate information on run-off factors to relate the fresh water flow contributed by the ungauged areas of the major watersheds, as well as that of the smaller, ungauged watersheds, to the recorded flow at the nearest gauging station.

Although, as noted earlier, there is some fresh water contribution to the Sound resulting from the two layered estuarine flow pattern in the East River, this flow would not be input as a boundary condition. If the hydrodynamic model adequately represents the physics of the motion and mixing in the coupled Long Island Sound - East River system, then the correct fresh water contribution to the Sound from the East River should be output by the model.

(d) Time history of wind velocity over the Sound is required for calibration and verification runs of the model.

Surface winds blowing over the surface of the Sound affect the residual current field and the time variations in the tidally averaged surface elevations in the Sound. Consequently, in order to compare model output with records of observed currents and water surface elevations, the real time distribution of wind velocity must be simulated in the model.

It is known that there are significant spatial variations in the wind field over the Sound. Wind velocity data is available for a number of locations around the shores of Long Island Sound, such that reasonably adequate estimations of the wind velocity field over the Sound for a given time period could be made. The confidence which could be placed in such estimates would be increased if a careful comparison were made between the land based wind velocity measurements and spot wind measurements made by survey vessels on the Sound.

There was not agreement as to whether a representative seasonal wind field needs to be simulated during production runs of the hydrodynamic model made to provide the velocity and diffusivity inputs to the water quality model.

(2) For the Water Quality Model

As in the case of data from the interior of the modeled waterway required for calibration and verification of the water quality model, there was insufficient time spent on the question of what water quality data is required at the open boundaries of the model for the participants to provide a complete set of recommendations concerning this matter. Consequently, it is again recommended that a special working group consider in detail the required program of data collection for the water quality modeling effort.

Some general, more or less obvious needs for data collection for use as boundary conditions at the open boundaries were identified by workshop participants. These included:

(a) Concentrations of water quality parameters, such as the several forms of phosphorus and nitrogen nutrients, BOD, metals and other toxic substances, in the various fresh water sources to the Sound.

(b) Mass emission rates from waste outfalls of substances of concern to water quality, including the substances listed in the just previous paragraph.

(c) Concentrations of the variables included in the water quality model, such as those listed in (a) above, at the open ocean boundaries.

(d) Any significant rates of input of toxic materials to the surface of the Sound from atmospheric fallout.

X. CONCLUSIONS AND RECOMMENDATIONS OF THE WORKSHOP

The following list is a summary of the consensus conclusions and recommendations of the workshop. In some cases where a clear consensus conclusion was not reached, alternate approaches are presented as suggestions by the workshop participants.

A. The recommended modeling strategy for the EPA LISES is to develop nested hydrodynamic and water quality models of Long Island Sound and its tributary estuaries. The hydrodynamic and water quality models would be coupled in the sense that the hydrodynamic model would provide velocity and diffusivity inputs to the water quality model.

B. In its ultimate form, the hydrodynamic model would itself be tightly coupled to a salinity submodel (essentially, a form of the water quality model for conservative constituents), which would be used to compute the time varying salinity distribution as a part of the hydrodynamic calculations. The salinity values would be used, together with data on the temperature distribution, in an equation of state to compute the density field, which in turn would be fed back into the calculations of the internal pressure force distribution as a part of the hydrodynamic calculations. The temperature distribution used in the equation of state would be entered as tabular values representing seasonally averaged observations of water temperature.

C. Useful interim results could be obtained using a less complex alternate to the procedure outlined in item B above. In this alternate representative seasonal averaged observed distributions of both temperature and salinity would be used to compute a density distribution, which would then be input to the hydrodynamic model to compute a steady state residual current field for each season.

D. The area to be simulated by the nested hydrodynamic model should include all of the East River, with the Battery as the western open boundary, all of Long Island Sound, and each of the important tributary estuaries and harbors on both shores of the Sound. In order to adequately simulate the tide in the Sound, the hydrodynamic model should be extended through Block Island Sound, such that the eastern open boundary would be a line extending from Montauk Point to Block Island, and thence to Point Judith.

E. The area to be simulated by the nested water quality model should also include all of the East River, with the Battery as the western open boundary. Because several of the water quality problems of immediate concern involve the Western Basin, the initial implementation of the water quality model might include only the western part of the Sound from Throgs Neck to a transect crossing the Sound at about Eatons Neck. However, there are also concerns about the combined effects of waste discharges from tributary estuaries and harbors bordering the Central and Eastern Basins. Hence ultimately the water quality model should be extended to include the entire Sound and all of the significant tributary estuaries and harbors.

F. The spatial complexity of the hydrodynamic and water quality models would not be uniform over all of the tidal waterways to be modeled. Sectionally averaged one-dimensional models should be adequate in the western part of the East River, from the Battery to Hells Gate. In the eastern reach of the East River, from Hells Gate to Throgs Neck, laterally averaged two-dimensional models would be required to adequately simulate the tidal and residual flow patterns of importance to the advection and mixing of materials of significance to the water quality of the East River and the western portion of the Sound. In some of the tributary estuaries along the Connecticut and Long Island shores, one-dimensional sectionally averaged models would suffice, while in some others laterally averaged two-dimensional models would be more appropriate. In some of the harbors bordering Long Island Sound vertically averaged two-dimensional models would be adequate for the purposes of the EPA LISES. A fully three dimensional model would be required for Long Island Sound itself, and may be required for some of the larger tributary waterways.

G. Note that for any given area to be simulated, both the hydrodynamic model and the water quality model should have the same spatial complexity. Also note that it is important that the various implementations of the models, that is, the models with different spatial complexity as applied to the various segments of the Sound and its tributary tidal waterways, be capable of being coupled one to the other.

H. The temporal complexity of the two models need not be the same. The hydrodynamic model should be exercised as a transient state model at tidal time scales. That is, the model should be driven by the rise and fall of the water surface characteristic of the real astronomical tide at the open ocean boundaries, and the time steps taken in the model runs should be small enough to resolve the periodic tidal rise and fall of the water surface and the ebb and flood of the tidal currents in the interior of the simulated waterway. The water quality model, on the other hand, can be exercised as a tidally averaged model, using as inputs values of velocity and diffusivity which have been averaged over the tidal period after being output from the hydrodynamic model.

I. Proper calibration and verification of the hydrodynamic model would require exercising this model with real time inputs of the variations in water surface elevations at the open boundaries, including both tidal and meteorological forced variations, with real time inputs of the surface wind stress over the Sound, and of the rate of fresh water inflow.

J. It was generally agreed that production runs of the hydrodynamic model could be made using a characteristic seasonal time histories for the tidally averaged variations of the water surface elevations, superimposed on the tidal variations, to drive the model at the open boundaries, and with characteristic seasonal variations in salinity at the open boundaries and in the rate of flow of the fresh water sources. It was also suggested that useful results could be obtained by using only tidal variations to drive the model at the open boundaries, with constant seasonally averaged values of the salinities at the open boundaries, and of the rate of flow of the fresh water sources.

K. There are several fully transient state three-dimensional hydrodynamic models in existance which could be adapted for use in the simulation of Long Island Sound. Some of these models are capable of being run as laterally integrated two-dimensional models or as vertically integrated two dimensional models, and so the coupling between the fully three-dimensional model of the Sound and the two-dimensional models of the tributary waterways should not pose any great difficulty.

L. Although three-dimensional water quality models have been developed and used in the study of lakes and estuaries, there has been very little work done on the use of a three-dimensional hydrodynamic model, with a second order turbulance closure submodel, to provide the fields of velocity and diffusivity for input to a three-dimensional water quality model. The existing hydrodynamic models suitable for use in the LISES all have salinity submodels, which, from the standpoint of the advective and diffusive processes, are of the same form as a water quality model. Consequently, most participants felt that the coupling of the hydrodynamic output into the water quality model could be readily accomplished, although some participants were not so convinced that this coupling could be easily made.

M. There was no consensus as to the cost of accomplishing the modeling effort as recommended, nor as to the time required to accomplish this task. However, several of the participants did indicate that the work of adaptation of existing three-dimensional hydrodynamic and water quality models for use in the simulation of Long Island Sound and its tributary waterways would require at least $400,000, and would require about three years to accomplish. This estimated cost does not include the cost of the field program recommended for obtaining the data needed for calibration and verification of the models, and needed to provide boundary data for production runs of the models.

N. Any models developed for use by the EPA LISES should be transferable for use by the federal and state management agencies. In order to attain this goal the source code must be written so that it is not machine specific, and there must be good documentation on the use of the model.

O. A conclusion that was immediately evident from the review of existing knowledge made for the workshop was that the LISES would benefit from the preparation of a report which would give a comprehensive analysis of existing published and unpublished data on circulation and property distribution in the Sound, and which also would present a critical review of the conclusions of past studies.

P. A mechanism should be established to provide effective coordination of the various sampling programs on the Sound to optimize the use of personel and survey vessels.

Q. For other conclusions and recommendations with regard to the data collection required for the modeling effort, see section IX, page 21, of this report.

APPENDICES

1. List of Participants
2. List of Observers

LONG ISLAND MODELING WORKSHOP

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