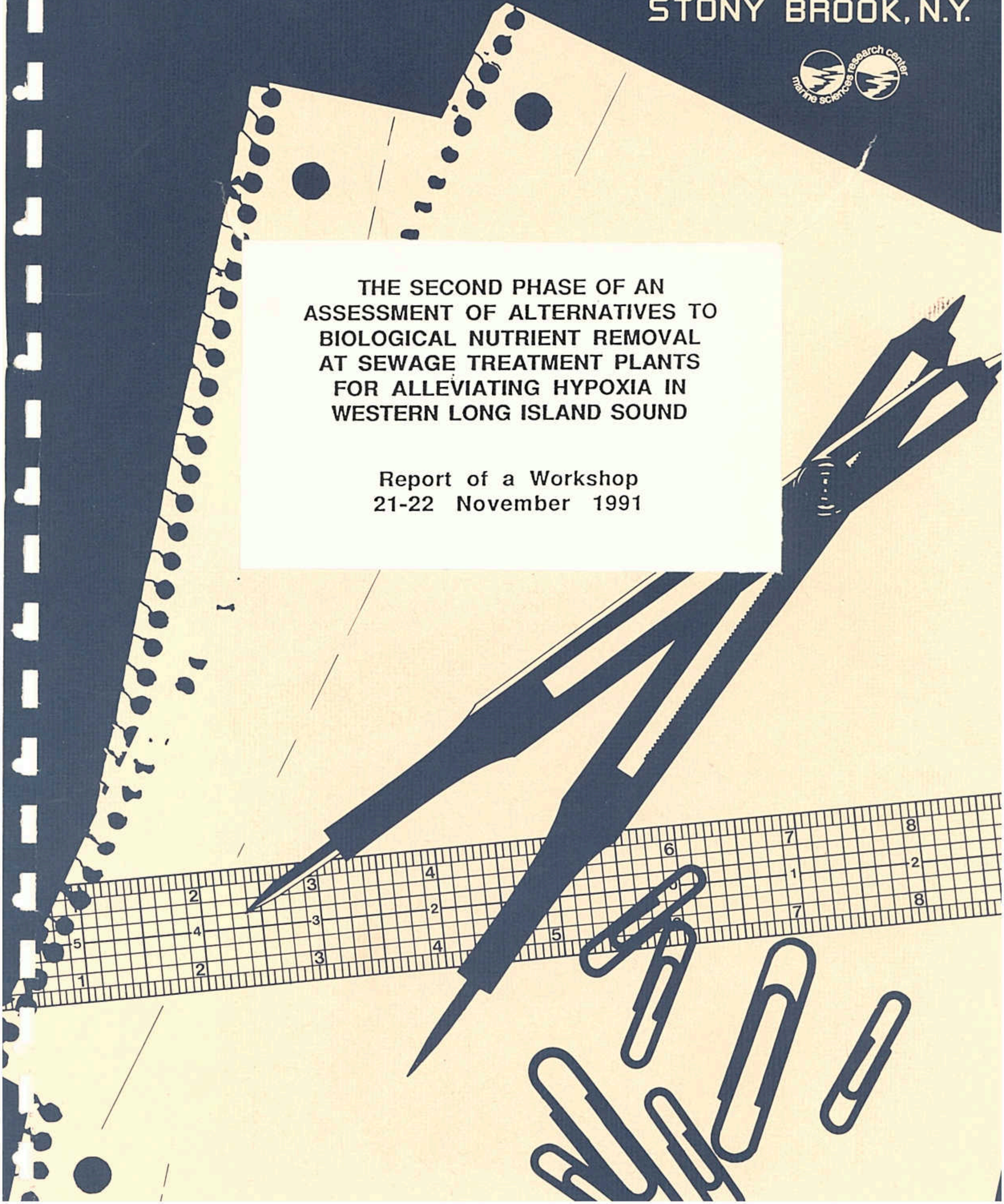
MARINE SCIENCES RESEARCH CENTER
STATE UNIVERSITY of NEW YORK
STONY BROOK, N.Y.



THE SECOND PHASE OF AN ASSESSMENT OF ALTERNATIVES TO BIOLOGICAL NUTRIENT REMOVAL AT SEWAGE TREATMENT PLANTS FOR ALLEVIATING HYPOXIA IN WESTERN LONG ISLAND SOUND

Report of a Workshop
21-22 November 1991

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Report of a Workshop
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COAST Institute

of the

Marine Sciences Research Center

J.R. Schubel
Project Director

Working Paper 56
Reference No. 91-19

Approved for Distribution

J.R. Schubel
Dean and Director

WORKSHOP PARTICIPANTS

Malcolm J. Bowman
Karen Chytalo
Robert Gaffoglio
Marty Garrell
Arthur Glowka
Eugenio Gomez-Reyes
Philip Hecklor
Xiaohang Huang
John Kilar
Kamazima Lwiza
Tadeusz Marchaj
Aslam Mirza
Jennie C. Myers
Philip O'Brien
Cynthia Pring-Ham
D.W. Pritchard
J.R. Schubel
John P. St. John
Malcolm Spaulding
Max Streib
R. Lawrence Swanson
Mark Tedesco
Peter Weyl
Robert E. Wilson
Charles Yarish

RAPPORTEUR

Doreen Monteleone
John M. Olin Fellow

LIST OF OBSERVERS

Melissa Beristain
Todd Echelman
Rafael Nino-Lopez
Arnoldo Valle-Levinson

INTRODUCTION

This workshop is the second of two workshops conducted at the request of the U.S. Environmental Protection Agency's Long Island Sound Study. The first workshop was held on 21 August 1991. The results of that workshop were summarized in MSRC Working Paper 53, Reference No. 91-11. The goals of the first workshop are summarized in Exhibit 1.

The second workshop was held on 21-22 November 1991. The participants and their affiliations are listed in Appendix A; the agenda for the workshop in Appendix B. The goals of the second workshop were to

- Reduce the list of alternatives identified in the first workshop; cull out the most promising.
- Enrich, expand, enhance the alternatives that survived.
- Outline some research priorities for completing an appropriate level of analysis of each surviving alternative.

The second workshop was structured around the series of commissioned white papers. The titles and authors of the commissioned white papers are summarized in Exhibit 2.

EXHIBIT 1

WORKSHOP I

20-21 November 1991

GOALS AND OBJECTIVES

Brief Recap

On 21 August 1991 a group met at MSRC (I) to identify alternatives to biological removal of nutrients at STPs to alleviate hypoxia in WLIS; (II) to select the alternatives with the greatest potential which should be evaluated more rigorously through the preparation of commissioned white papers; and (III) to identify candidates to author these white papers.

I. Alternative Approaches to Biological Nutrient Removal at STPs.

- Relocation of outfalls of selected STPs.
- Modification of basin geometry of LIS to alter circulation and flushing.
- Construction of structures to alter the circulation and flushing of LIS.
- Softer solutions -- construction of wetlands and floating farms.
- Localized vertical turbulence generators.
- Strategies to reduce the influents to STPs.
- Strategies to reduce the effluents (vol., nutrients and their impacts from STPs.
- Assessment of the effects of level of treatment at STPs on the environment.
- Selected for preparation of commissioned white papers.

II. Most Promising Alternatives

- Relocation of outfalls of selected STPs.
- Modification of basin geometry of LIS to alter circulation and flushing.
- Construction of structures to alter the circulation and flushing of LIS.
- Softer solutions -- construction of wetlands and floating farms.
- Strategies to reduce influents (i.e. water conservation) to STPs.
- Assessment of the effects of different levels of treatment on environmental quality with special emphasis on assessing the effects of the upgrading NYC's sewage treatment plants to secondary on D.O. in Western LIS.

EXHIBIT 2

TITLES AND AUTHORS OF WHITE PAPERS INCLUDED IN THIS REPORT

TITLE	AUTHOR
COMMISSIONED WHITE PAPERS	
Preliminary Assessment of Relocation of Outfalls From Selected Sewage Treatment Plants to Alleviate Hypoxia in Western Long Island Sound	John P. St. John
Structures to Reduce or Eliminate Hypoxia in Western Long Island Sound	Malcolm J. Bowman
Influence of Basin Morphology on Circulation and Mixing in Long Island Sound	Robert E. Wilson
Can Seaweed Farms Alleviate Hypoxia in Western Long Island Sound?	Valrie A. Gerard
Use of Constructed Wetland Technology for Treatment of Stormwaters and Wastewater Effluent: Summary of Considerations and Potential Applications to Alleviate Seasonal Hypoxia in Western Long Island Sound	Jennie C. Myers
Water Conservation Measures and Their Effect on Sewage Treatment and Hypoxia in Long Island Sound	R. Lawrence Swanson Anne Mooney
The Impact of Improved Sewage Treatment in the East River on Western Long Island Sound	R. Lawrence Swanson Anne West-Valle Marci Bortman Arnoldo Valle-Levinson Todd Echelman
Others	
Aquaculture Methods For Use in Managing Eutrophicated Waters	John Merrill John Kilar Xiaohang Huang Charles Yarish
Tide Gates As Means of Alleviating Hypoxia in Western Long Island Sound and Reducing Water Pollution in New York/New Jersey Harbor Waters	Tadeusz J. Marchaj

All of the commissioned white papers that were prepared for the workshop are included in Appendix C of this report. One additional white paper (Aquaculture Methods for Use in Managing Eutrophicated Waters) was distributed at the workshop and is included in Appendix D. An additional white paper that was received after the workshop is included in Appendix E.

The author of each commissioned white paper made an approximately 20 minute presentation summarizing the major conclusions concerning contributions that specific technology might make to reducing the levels of nutrients in the Sound and any other environmental benefits or costs it might have. Each author also outlined the kinds of research needed to reduce the level of uncertainty associated with the application of the technology to Long Island Sound.

After all the presentations were completed, the next step was to determine which of the alternatives had the greatest promise for contributing to a comprehensive strategy for reducing the levels of nutrients in the Sound. Each workshop participant was given 4 votes (colored stickers) and instructed that he or she could spread the votes among the seven candidate strategies in any way he or she chose: all for one strategy, one for each of four different strategies, etc. The results of the balloting are summarized in Table 1. Based upon the results of the voting, three strategies (3, 5, 7) were put in a stand-by category. Most of the remainder of the workshop was spent discussing the four most highly ranked strategies to refine them, to enhance them, and to identify what research efforts should be carried out to clarify the contributions each might and to reduce the likelihood of unanticipated and undesirable environmental surprises, if any were implemented.

TABLE 1

Results of Balloting to Identify the Alternatives with The Greatest Potential for Contributing to a Strategy to Reduce Nutrient Levels in Long Island Sound

	Strategy	Number of Votes
1.	Relocation of Outfalls	20
2.	Tidal Gates	28
3.	Modification of Basin Geometry	7
4.	Wetland Construction	25
5.	Floating Seaweed Farms	7
6.	Clarification of the Role of Increases -- Past and Proposed -- in the Level of Treatment at STPs in Changing Environmental Quality	24
7.	Wild Card* Diversion of Nutrient-Rich Water to Nutrient-Deficient Areas, plus Other Complementary Activities.	1
	Total votes	112

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*Unsolicited and presented at the workshop; see Appendix E for summary

Before the ranking of alternative strategies was made, one strategy -- reducing the influent to sewage treatment plants through water conservation -- was taken off the list. All workshop participants felt that the reasons for water conservation were so compelling that it should be promoted aggressively. The reasons for aggressive water conservations include environmental benefits that extend far beyond wastewater management. In terms of the theme of this particular workshop, the primary benefits of reduced flow to STPs are that the increase in retention times within plants promotes removal of nitrogen through the nitrification-denitrification cycle and the reduced flow mitigates to some degree, the inputs of combined sewer overflows (CSOs.)

A special note concerning the potential of seaweeds as a mechanism for reducing nutrients levels is in order. The white paper commissioned on seaweeds was commissioned to evaluate <u>only</u> the potential of floating seaweed farms as a strategy for controlling nutrient levels in the Sound. The author concluded, and workshop participants concurred, that the potential of floating seaweed farms in this application is small. It was pointed out that we may have constrained the potential role of seaweed in reducing nutrient levels too narrowly by restricting attention to floating seaweed farms. A second white paper on seaweeds (Merrill et al. 1991, included in Appendix D), was distributed at the workshop and was discussed briefly, but was not evaluated relative to the other alternatives.

SOME GLOBAL RECOMMENDATIONS

In addition to the specific recommendations associated with each of the various alternative technologies, the participants formulated several general, more global, recommendations that cut across all alternatives. These are summarized below.

Recommendation 1. Before launching a full-scale biological nutrient removal (BNR) program costing billions of dollars, the strategies outlined in this report -- particularly the most highly ranked strategies -- should be evaluated more rigorously. Some may be cost effective and have multiple benefits.

Recommendation 2. There is no silver bullet for reducing nutrient levels in LIS. The best -- most effective -- strategy may be a combination of strategies with each mix of strategies being tailored to the conditions of the specific sub-environment.

Recommendation 3. There must be a continued and strengthened commitment by New York and Connecticut and by the federal government to increase the level of understanding of the natural processes that characterize LIS, of how society has affected those processes and of how those effects have been manifested in changes of environmental values important to society. Compared with most of the nation's other major estuaries, the data and information base for the Sound is poor. This not only is true of data to establish historical trends, but of existing conditions. Even some of the most basic information is lacking, or at least has not been analyzed, interpreted and synthesized into forms that are accessible to potential user groups.

Some of the fundamental questions which have not been answered include, What are the critical resources? What are the critical habitats? What resources are at-risk? What organisms live where and when? This commitment to a program of fundamental research should not neglect those species important to the general public: finfish, shellfish, marine mammals and birds. This situation of an impoverished knowledge base is ironic when one considers that the Sound serves more people than any other U.S. estuary and that its recreational value is probably greater than that of any U.S. estuary.

<u>Recommendation 4.</u> In evaluating the two engineering alternatives described in this report -- relocation of outfalls and tide gates across the East River -- a special effort should be made to identify those studies which will be required for both. A number of the same questions will need to be answered for both, although their consequent environmental effects on properties and processes of LIS other than nutrients and dissolved oxygen may be very different.

<u>Recommendation 5</u>. The present regulatory/legal/institutional framework should not be allowed to inhibit evaluation of the strategies outlined in this report. It should also be recognized that if some of these strategies were to be implemented in the future, it might require significant changes in the regulatory/legal/institutional framework.

RESEARCH NEEDS

A significant research effort will be required to properly evaluate any of the strategies outlined in this workshop report. Some of the research needed is described in each of the white papers. Other research topics are summarized, by alternative technology, in this section.

Relocation of Outfalls

- Develop a system-wide water quality model (Harbor-Sound-Bight)
- Calibrate the model with available data
- Collect additional field data for model refinement
- Apply models to evaluate of relocation requirements and adverse impacts
- Assess effects on living marine resources and habitats
- Conduct engineering feasibility studies
- Elucidate the processes that control the exchange of dissolved and particulate species between the bottom and the over-lying waters. Knowledge of these processes is needed to accurately model the environmental effects of relocating outfalls -- both in the areas from which they would be removed and the areas to which they would be transferred.
- Assess what effects the relocation of outfalls to various locations in the Lower Bay of New York Harbor would have on the gravitational circulation of the Harbor and the Hudson River estuary.

- Assess the public's reaction to such proposals and to determine the conditions under which states and local communities have been successful in securing public support for engineering projects of this magnitude.
- Identify the resources that would be at risk from such a strategy and how those risks might be eliminated, reduced or mitigated.
- Assess the effects of relocating discharges to the Lower Bay on the migration of anadromous and catadromous through the area.
- Assess the effects of an ocean outfall on whales migrating past Long Beach.
- Assess any possible negative effects of large scale removal of nutrients from the Sound, effects on phytoplankton and on phytoplankton-benthos coupling.
- Assess the adequacy of the existing models to deal with biological response questions. For example, do they include enough phytoplankton species? If not, the models should be improved through collaborative efforts.
- Establish the importance that variability at different time and space scales has on LIS.

Tide Gates

- Select the most appropriate combination of existing models needed to evaluate the effects of tide gates on the circulation, salinity field nutrients distribution and dissolved oxygen of the Sound and contiguous waters on both a seasonal and a year-round basis.

- Assess the adequacy of these models. If necessary, upgrade them. [The feeling was that we almost have a fully three-dimensional coupled hydrodynamic - water quality model that could be used to evaluate this strategy.]

- Assess the impact on migrating fish and on other marine life.

- Evaluate socio-economic issues including impacts on shipping and transportation.

- Research to assess the effects on New York Harbor and the Hudson River estuary of diverting saltier, more contaminated water into this environment.

- The modelling needed to evaluate this strategy requires greater detail than that needed to evaluate the effects of the relocation of outfalls.

- Research to assess the effects of tide gates on the salinity field and the gravitational circulation of LIS, particularly the western Sound.

- Research to assess the biological effects of the predicted changes in salinity.

Construction of Wetlands

Storm Water

- Review how wetlands have been used in other systems and assess the applicability of the transfer of the technology to the LIS system.

- Review the modelling efforts associated with wetlands (e.g., the flow over and through them) to assess the transferability of this knowledge to the LIS situation.

- Assess how the use of wetlands for storm water management affects the environmental quality of the marsh, particularly the sediments, and what the implications are for groundwater and surface water contamination, uptake by plants and transfer to other components of the food web.

- Assess how the seasonality of a marsh would affect their usefulness in controlling nutrient inputs to the Sound, particularly during summer when hypoxia is a problem.

- Assess how much nitrogen existing wetlands are extracting and the fate of that nitrogen.

- Review the literature on the modelling of nutrient dynamics, particularly nitrogen, in marshes and assess its adequacy for the LIS situation.

- Inventory the natural wetlands in the LIS drainage basin and prepare maps (preferably a GIS) that documents where they are, how extensive, their distinguishing characteristics, etc.

- Inventory the locations, strengths and special characteristics of the major point and non-point sources of nutrients to LIS.

- Inventory sites that have the potential for construction of wetlands; match them up with sources of nutrients. Take advantage of the work being conducted by the non-point source working group and others.

- Select an appropriate sub-watershed area for a case study to assess the efficacy of the proposed strategy.

- Design and conduct pilot field studies to feed into the case study.

- Scale up to a feasibility demonstration project of a larger area and carry out the demonstration.

- Design and conduct a monitoring program to assess the efficacy of the actions taken.

- Assess the costs and benefits of a harvesting versus a non-harvesting strategy.

Wastewater

- Inventory existing wetlands in the vicinity of sewage treatment plants.

- Inventory sites near sewage treatment plants that are potential sites for construction of wetlands.

- Assess how much nitrogen existing wetlands are extracting and the fate of that nitrogen.

- Review what has been done in the northeast and in other regions and assess its applicability to the Long Island situation. Three wetlands have been created in the northeast for wastewater treatment.

- Evaluate the costs and benefits of sub-surface and free surface flow strategies for managing wastewater effluent with wetlands with specific reference to conditions in the LIS watershed.

- Move from assessment to design to a pilot study to a demonstration project carefully tailored to the characteristics of a particular sewage treatment plants.

- The use of wetlands for wastewater treatment should be evaluated as a component of a larger, more comprehensive mix of management strategies.

- Assess the costs and benefits of a harvesting vs. a non-harvesting strategy.

Research Needs Not Specific to Any Technological Alternative

•Each municipality's water and wastewater programs need to be considered as components of a single system. This may require administrative changes.

•A critical assessment needs to be made of the effects of sewage sludge dewatering facilities located on the East River and in other coastal regions around the Sound. The nutrient-enriched effluent could have major undesirable impacts on the Sound, or other coastal waters, if it is released into them. Efforts being made to reintroduce this nitrogen back into the sludge to enhance its value as a fertilizer should be promoted. Could this nutrient-enriched effluent be diverted to wetlands? ... to a tunnel that would carry the discharges of outfalls to a point farther seaward?

•Simple and inexpensive ways of enhancing nutrient removal at sewage treatment plants should be explored and pursued. These include the increase of retention time of wastewater at sewage treatment plants to promote nitrification-denitrification.

•More sophisticated measures of hypoxia are required than simple measures of minimum levels of dissolved oxygen. Areas and volumes that are affected need to be documented.

- Greater attention needs to be devoted to assessing how environmental changes affect the organisms of greatest interest to the public -- fish, shellfish, waterfowl, shore birds and marine mammals.

- Document how the species diversity of LIS has changed over time. Has it declined? If so, what kinds of species have dropped out and why?

- Examine the apparent shift of the timing of the spring bloom to later in the year. Is it real? If so, what is the most plausible explanation?

- Far more attention needs to be devoted to producing a richer literature on the natural history of LIS for the general public. Compared to other major estuaries (e.g. the Chesapeake Bay), the literature on the Sound is impoverished.

- Far greater attention should be directed at synthesizing, analyzing and interpreting historical data sets that could provide new insights into the changes that have occurred in the Sound and its watershed over the period of historical records and of what may have caused those changes. Special attention needs to be devoted to climatological data and the role that climatology has played in hypoxia.

APPENDICES

APPENDIX A:

WORKSHOP PARTICIPANTS

Dr. Malcolm J. Bowman
Marine Sciences Research Center
The State University of New York
Stony Brook, NY 11794-5000

Ms. Karen Chytalo
New York State Department
of Environmental Conservation
Division of Marine Resources
Building 40
State University of New York
Stony Brook, NY 11790-2356

Mr. Robert Gaffoglio
New York City Department
of Environmental Protection
Bureau of Environmental Engineering
96-05 Horace Harding Expressway
Corona, NY 11368

Mr. Marty Garrell
Adelphi University
Department of Physics
Box 701
Garden City, NY 11530

Mr. Arthur Glowka
Long Island Sound Task Force
Stamford Marine Center
185 Magee Avenue
Stamford, CT 06902

Mr. Eugenio Gomez-Reyes
HydroQual, Inc.
One Lethbridge Plaza
Mahwah, NJ 07430

Mr. Philip Hecklor
Deputy Director -
Program Management
New York City Department
of Environmental Protection
96-95 Horace Harding Expwy.
Corona, NY 11368

Dr. Xiaohang Huang
Deputy Director -
Department of Botany
Institute of Oceanology
Academia Sinica
7 Nanhai Road
Qingdao, China

Mr. John Kilar
University of Connecticut
at Stamford
641 Scofieldtown Rd.
Stamford, CT 06903

Dr. Kamazima Lwiza
Marine Sciences Research Center
State University of New York
Stony Brook, NY 11794-5000

Mr. Tadeusz J. Marchaj
Preload, Inc.
839 Stewart Avenue
Garden City, NY 11530

Mr. Aslam Mirza
New York State Department
of Environmental Conservation
50 Wolf Road
Albany, NY 12233-3503

Ms. Jennie C. Myers
13 Standish St.
Cambridge, MA 02138

Mr. Philip O'Brien
New York State Department
of Environmental Conservation
50 Wolf Road
Room 328
Albany, NY 12233-3503

Ms. Cynthia Pring-Ham
U.S. EPA
Region I
WQE-425
JFK Building
Boston, MA 02203

Dr. D.W. Pritchard
401 Laurel Drive
Severna Park, MD 21146

Dr. J.R. Schubel
Dean and Director
Marine Sciences Research Center
The State University of New York
Stony Brook, NY 11794-5000

Mr. John P. St. John
HydroQual, Inc.
One Lethbridge Plaza
Mahwah, NJ 07430

Mr. Malcolm Spaulding
University of Rhode Island
Ocean Engineering
Kingston, RI 02991

Mr. Max Streib
New York State Department
of Environmental Conservation
Division of Marine Resources
Bureau of Marine Habitat Prot.
Building 40/SUNY
Stony Brook, NY 11794

Dr. R. Lawrence Swanson
Marine Sciences Research Center
Waste Management Institute
The State University of New York
Stony Brook, NY 11794-5000

Mr. Mark Tedesco
EPA Region II
Jacob K. Javits Federal Bldg.
26 Federal Plaza
New York, NY 10278

Dr. Peter Weyl
Marine Sciences Research Center
The State University of New York
Stony Brook, NY 11794-5000

Dr. Robert E. Wilson
Marine Sciences Research Center
The State University of New York
Stony Brook, NY 11794-5000

Dr. Charles Yarish
University of Connecticut
641 Scofieldtown Rd.
Stamford, CT 06903

RAPPORTEUR

Doreen Monteleone
Marine Sciences Research Center
The State University of New York
Stony Brook, NY 11794-5000

LIST OF OBSERVERS

Melissa Beristain
Sea Grant Extension
The State University of New York
Stony Brook, NY 11794-5001

Todd Echelman
Marine Sciences Research Center
The State University of New York
Stony Brook, NY 11794-5000

Rafael Nino-Lopez
Marine Sciences Research Center
The State University of New York
Stony Brook, NY 11794-5000

Arnoldo Valle-Levinson
Marine Sciences Research Center
Waste Management Institute
The State University of New York
Stony Brook, NY 11794-5000

ALTERNATIVE TECHNOLOGIES WORKSHOP II

21-22 November 1991
Marine Sciences Research Center
Challenger 165

GOALS OF WORKSHOP: Using the commissioned white Papers as our point of departure, the goals of the workshop are

(1) to identify what additional research and analysis, if any, are required to evaluate rigorously the scientific, engineering and economic potential of each alternative explored by a white paper and

(2) to recommend, if at this stage, any of these strategies should be included in the CCMP for hypoxia management, or if additional research is needed, or...

1000 Sharp	Welcome, Introductions and Overview and Objectives for the Day	Cynthia Pring-Ham J.R. Schubel
1030	Recap of Results of First Workshop	J.R. Schubel
1100	Brief Summaries of White Papers* (20 minutes for each presentation and 10 minutes for initial discussion)	
	A. Relocation of Outfalls from Selected Sewage Treatment Plants	John St. John
	B. Modifications of Basin Geometry to Alter Circulation and Flushing	Robert Wilson
1200	Lunch	
1300	Continued Overviews and Discussion of White Papers	
	C. Structures to Change Circulation and Mixing	Malcolm Bowman

* It is expected that the workshop participants will have read the white papers.

	D. The Softer Solutions -- Construction of Wetlands	
	1. The Softer Solutions -- Construction of Wetlands	Jennie Myers
	2. The Softer Solutions -- Floating Seaweed Farms	Valrie Gerard
1430	Break	
	E. Reduce the Influent to Sewage Treatment Plants	Larry Swanson
	Break	
	F. Reduce the Level of Treatment at NYC's Treatment Plants	Larry Swanson
1530	Break	
1600	Narrowing the Options	J.R. Schubel, Facilitator
1630	Sharpening the Focus of the Strategies Still Under Consideration... Six Hats Thinking	
1800	Adjourn	
	Dinner on Your Own	

ALTERNATIVE TECHNOLOGIES
WORKSHOP II

November 22, 1991

0800	Continental Breakfast in Challenger 165
0830	Six Hats Thinking Continued
1000	Break
1015	Discussion Continued
1100	Identification of Some Research Questions and Elements of a Research Program for Projects Still Under Consideration
1230	Working Lunch Formulation of Conclusions and Recommendations of Workshop
1430	Adjourn

APPENDIX C

COMMISSIONED WHITE PAPERS

Preliminary Assessment of Relocation of Outfalls From Selected Sewage Treatment Plants to Alleviate Hypoxia in Western Long Island Sound

by

John P. St. John

Structure to Reduce or Eliminate Hypoxia in Western Long Island Sound

by

Malcolm J. Bowman

Influence of Basin Morphology on Circulation and Mixing in Long Island Sound

by

Robert E. Wilson

Can Seaweed Farms Alleviate Hypoxia in Western Long Island Sound?

by

Valrie A. Gerard

Use of Constructed Wetland Technology for Treatment of Stormwaters and Wastewater Effluent: Summary of Considerations and Potential Applications to Alleviate Seasonal Hypoxia in Western Long Island Sound

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Jennie C. Myers

Water Conservation Measures and Their Effect on Sewage Treatment and Hypoxia in Long Island Sound

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R. Lawrence Swanson
Anne Mooney

The Impact of Improved Sewage Treatment in the East River on Western Long Island Sound

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Preliminary Assessment of Relocation of Outfalls From Selected Sewage Treatment Plants to Alleviate Hypoxia in Western Long Island Sound

by

John P. St. John

Influence of Basin Morphology on Circulation and Mixing in Long Island Sound

by

Robert E. Wilson

INFLUENCE OF BASIN MORPHOLOGY ON CIRCULATION AND MIXING IN LONG ISLAND SOUND

by

Robert E. Wilson
Marine Sciences Research Center
State University of New York
Stony Brook, NY 11794-5000

ABSTRACT

Selected topics concerning the effects of basin morphology on circulation and mixing are discussed. From these discussions inferences can be drawn regarding possible effects of changes to basin morphology. The topics include: the influence of Mattituck Sill on both deep water renewal and tidal motion in the Sound; the influence of Stratford Shoal and nearby coastal promontories on circulation and exchange in the western basin; the influence of the East River on fresh water intrusion into the western Sound.

INTRODUCTION

Long Island Sound is an elongated partially-enclosed body of water; it is approximately 135 km long and 30 km wide at its widest point. At the eastern end the width decreases to approximately 16 km. The mean depth of the basin is approximately 22 m, and it is characterized by relatively strong topography and prominent morphological features such as sills, coastal headlands and shoals (Figure 1). The Sound exhibits some estuarine characteristics including appreciable horizontal salinity gradients and strong tidal streams. Semidiurnal tidal streams approach 250 cm/s in the eastern passes. The eastern end of the Sound remains at near oceanic salinities, and the western end remains at reduced salinities because of the discharge of the Hudson River. In addition there is a substantial freshwater discharge from rivers in Connecticut. The imposed longitudinal salinity gradient plus the direct freshwater discharge maintains a gravitational circulation pattern. Riley (1952) realized that both density driven and tidal residual currents (produced by the interaction of tidal currents with the basin topography) contribute to residual circulation.

An excellent introduction to the basic hydrography of the Sound is presented by Koppelman et al (1976) and Hardy (1971). Included are discussions concerning the influence of the rather unique basin morphology on circulation.

This paper has as its limited objectives a description of the influence of selected morphological features on circulation

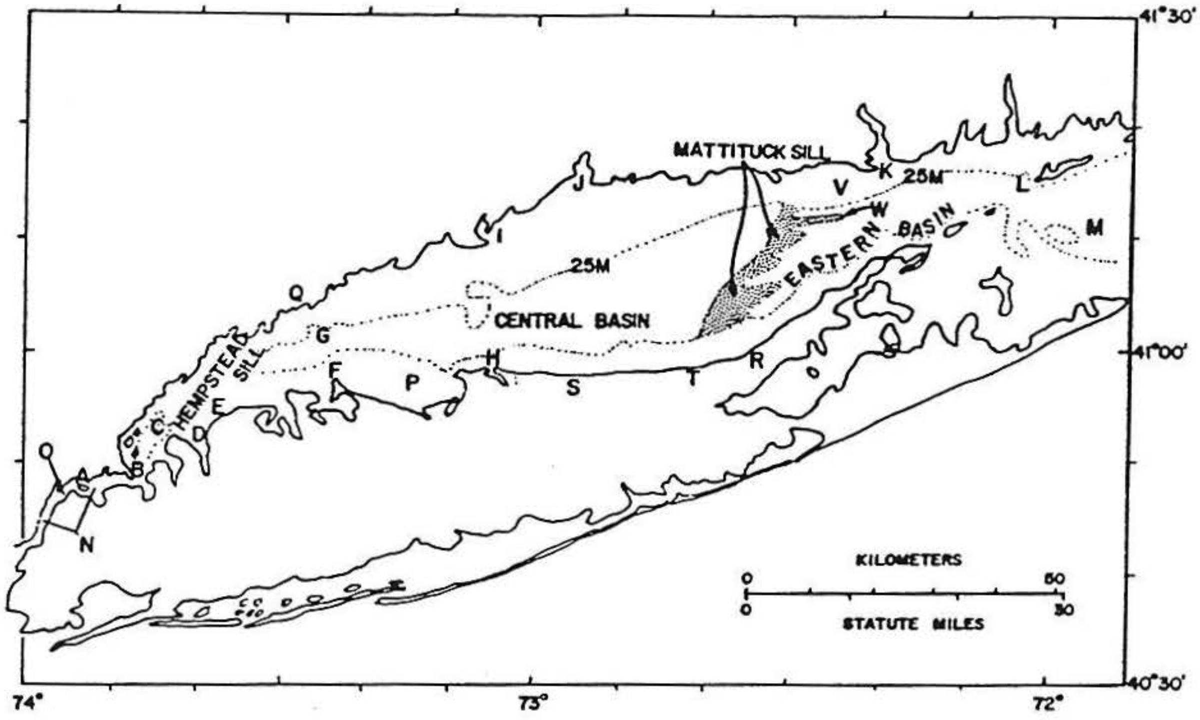


Fig. 1. Geographic features of Long Island Sound.

A.	Rikers Island	I.	Housatonic River	Q.	Stamford, Conn.
B.	Throgs Neck	J.	New Haven Harbor	R.	Mattituck
C.	Execution Rock	K.	Connecticut River	S.	Shoreham
D.	Hempstead Harbor	L.	The Race	T.	Roanoke Point
E.	Matinicock Point	M.	Block Island Sound	U.	Area of Sill Depth Maximum (24 m)
F.	Eatons Neck	N.	East River		
G.	Cable & Anchor Reef	O.	Hell Gate	V.	Long Sand Shoal
H.	Port Jefferson	P.	Smithtown Bay	W.	Six Mile Reef

Figure 1. Geographic features of Long Island Sound (from Hardy, 1971).

and mixing in the basin. From this description inferences can be drawn regarding changes which might occur were a particular feature modified.

The discussions include: 1) the influence of Mattituck Sill on deep water renewal and tidal motions in the Sound, 2) the influence of Stratford Shoal on residual circulation patterns, 3) the influence of coastal promontories on circulation in the western basin, 4) Hempstead Sill and deep water intrusion, 5) the influence of the East River on fresh water intrusion into the western Sound.

MATTITUCK SILL

Mattituck Sill is a submarine ridge which separates the eastern and central basins. The average depth of the sill is approximately 20 m; the maximum depth of 24 m occurs northwest of Mattituck Inlet. The central and eastern basins have channel depths which exceed 30 m, so the sill represents an elevation of approximately 10 m.

INFLUENCE ON DEEP WATER RENEWAL

Hardy (1971) has described spatial differences in distributions of salinity, temperature and dissolved oxygen in the vicinity of the sill. Horizontal distributions at 25 m (Figure 2) indicate that the ridge limits the intrusion of high salinity, low temperature and well oxygenated water into the central basin in

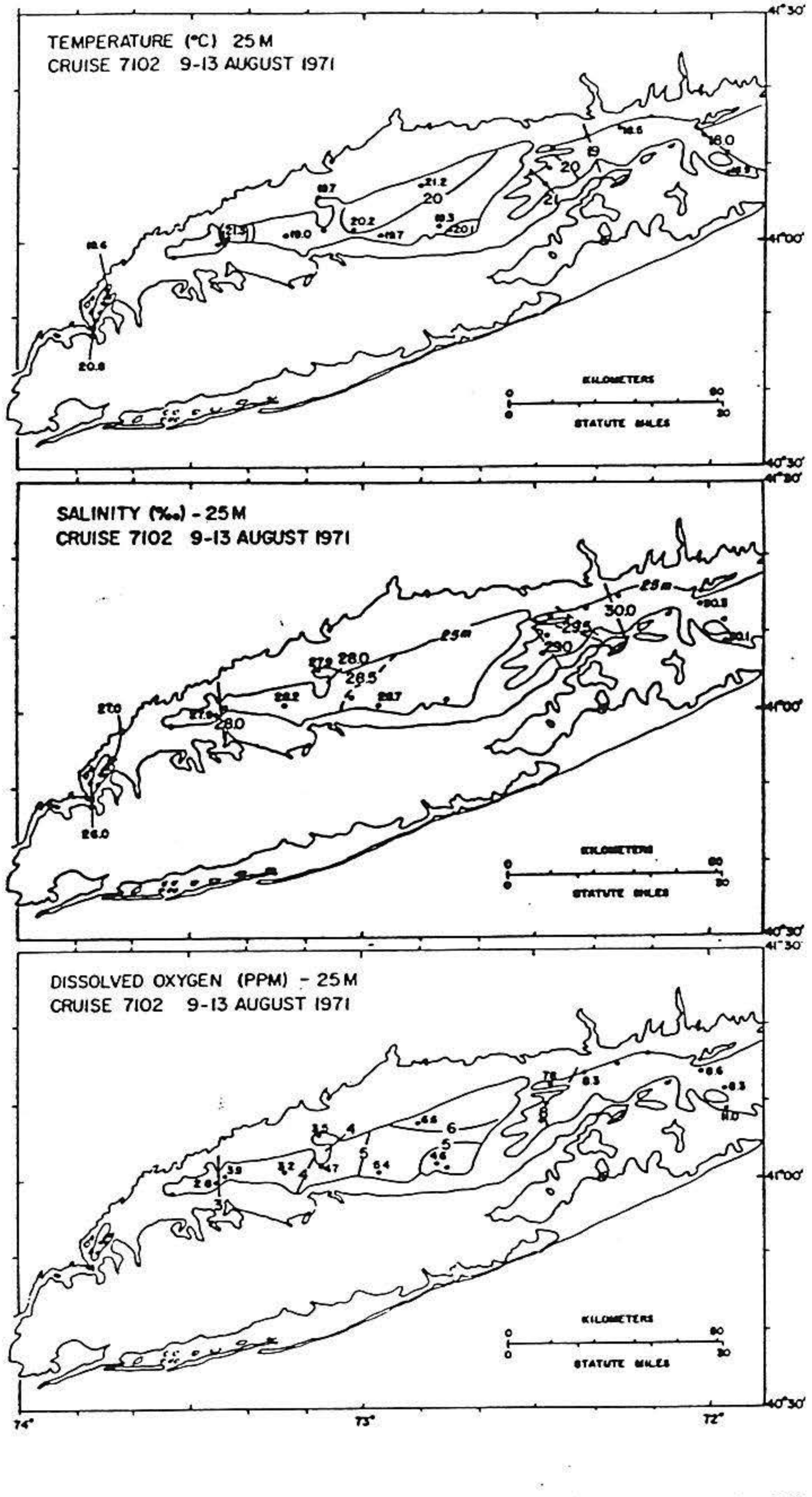


Figure 2. Temperature, salinity and dissolved oxygen at 25 m depth (from Hardy, 1971).

summer.

Recent NOS modelling results (Figure 3) emphasize the influence of the sill on the intrusion of shelf waters, both because of its elevation and because of enhanced tidal mixing. The simulations suggest that the deep water intrusion which does occur commences in late winter as surface heating begins to suppress mixing.

The process by which deep water intrudes from the shelf is best interpreted in terms of gravity current motion. A characteristic density difference between waters within the central basin and eastern basins is approximately 2 sigma-t units. In water 30 m deep this gives 38 cm/s as a gravity current speed. Observed intrusion velocities are actually much lower than this, partly because of friction. This is important because flows for which the velocity is lower than the gravity current speed (characterized as "subcritical") are subject to blocking by bottom obstacles.

Some insight into the influence of the sill bathymetry on the intrusion of deep water can be obtained from simple simulations. Results from a lock experiment for bathymetry characteristic of the eastern Sound (Figure 4) emphasize that significant blocking occurs at depths below approximately 26 m. Figures 5 and 6 show salinity distributions at 26 m, 32 m, 37 m, and 43 m at 5 hours after the withdrawal of a lock separating waters of 20 and 21 parts per thousand located to the right of the dashed domain (Figure 4). Simulations (not presented) for a modified bathymetry in which a portion of the sill was removed down to a

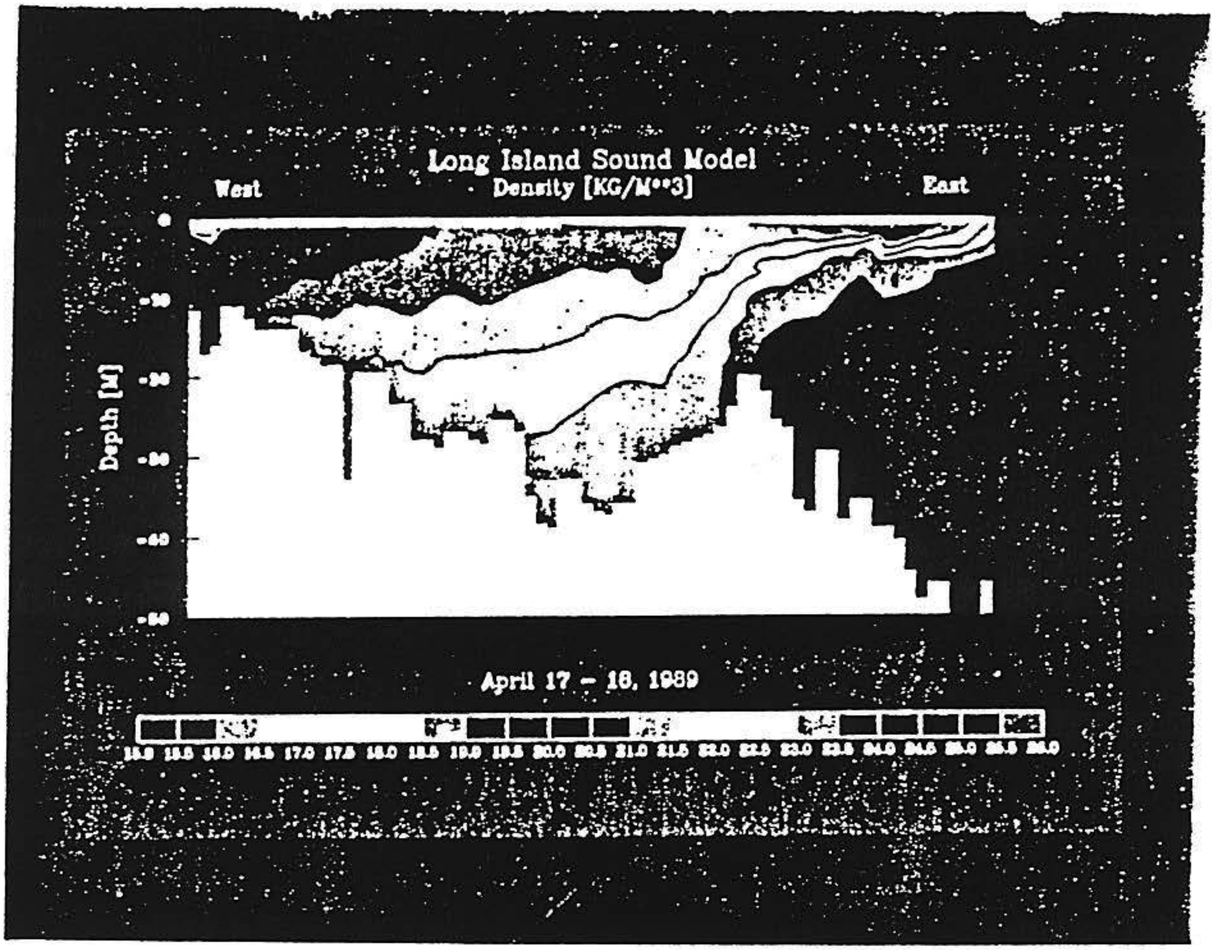


Figure 3. Vertical density section from NOS Long Island Sound model corresponding to conditions on April 17-18, 1989.

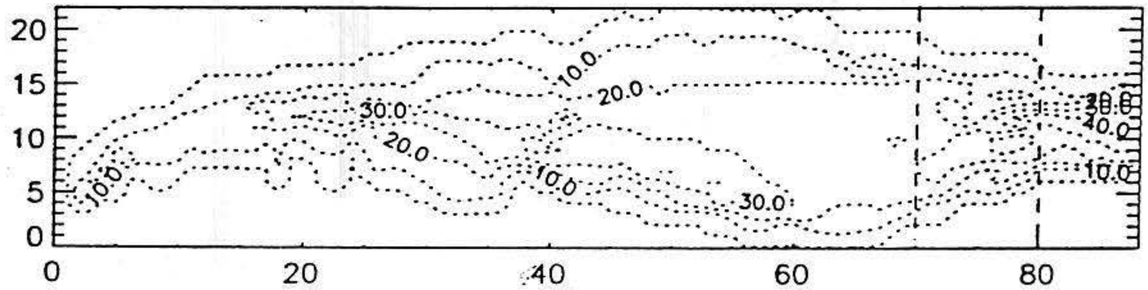


Figure 4. Domain for lock experiment (dashed lines) in vicinity of Mattituck Sill (see text).

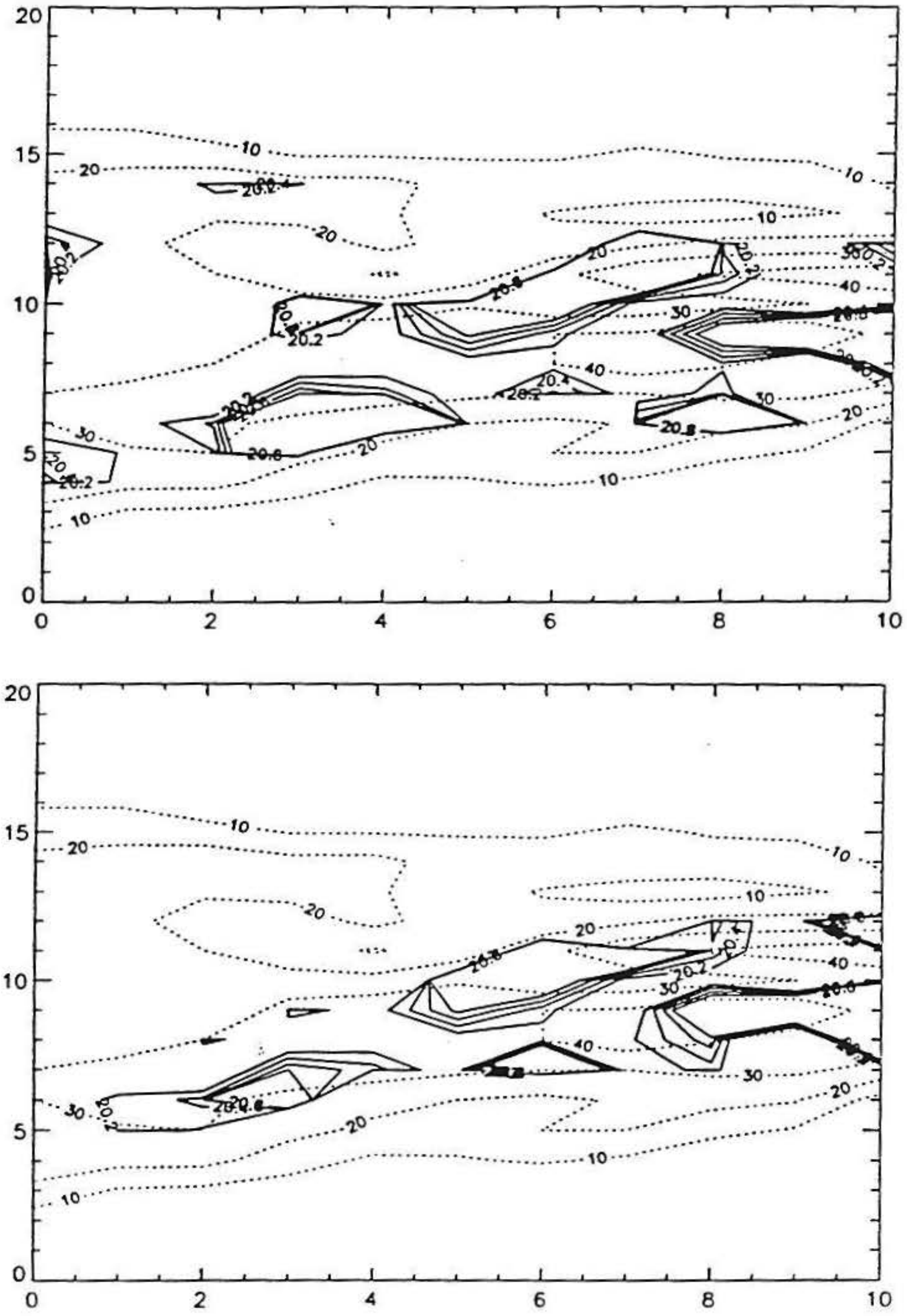


Figure 5. Salinity contours at 26 m depth (upper) and 32 m depth (lower) within domain defined by dashed lines in Figure 4.

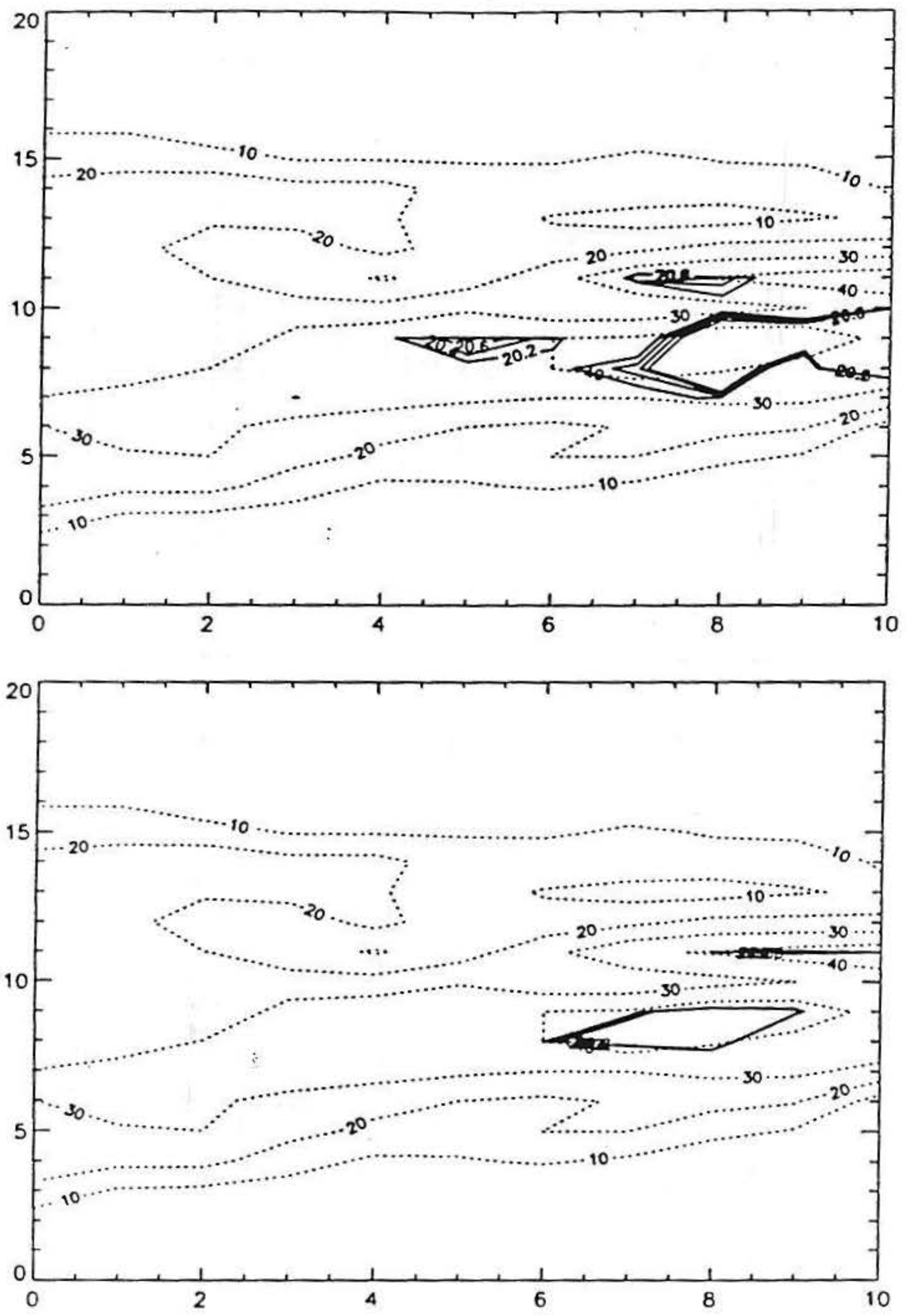


Figure 6. Salinity contours at 37 m depth (upper) and 43 m depth (lower) within domain defined by dashed lines in Figure 4.

depth of 30 m show a rapid intrusion of deep saline water through the channel.

It should also be mentioned that major modifications to sill bathymetry could alter the characteristics of tidally induced vertical mixing which is now relatively intense over the sill.

INFLUENCE ON BAROTROPIC TIDES

The barotropic tide in Long Island Sound has been described in terms of resonant cooscillation (Redfield, 1950; Swanson, 1971; Spaulding and Beauchamp, 1983). The mean range for the semidiurnal tide (Figure 7) is approximately 1 m on the adjacent shelf; it decreases to approximately 0.67 m within Block Island Sound and then increases threefold to over 2 m in the western Sound.

The phenomenon of resonant cooscillation which has been proposed to explain the amplification of tides in the Sound is based simply on the interference of two damped progressive waves travelling in opposite directions. Resonance occurs when the basin length is approximately one quarter of the local tidal wavelength. Resonance therefore depends on the basin length and its mean depth. More recently, however, Chant and Wilson (1991) have shown that the longitudinal distribution of tidal range and phase (Figure 8) are not consistent with quarter wave resonance but rather with Helmholtz resonance. This is important because it means that overall characteristics of tides are relatively

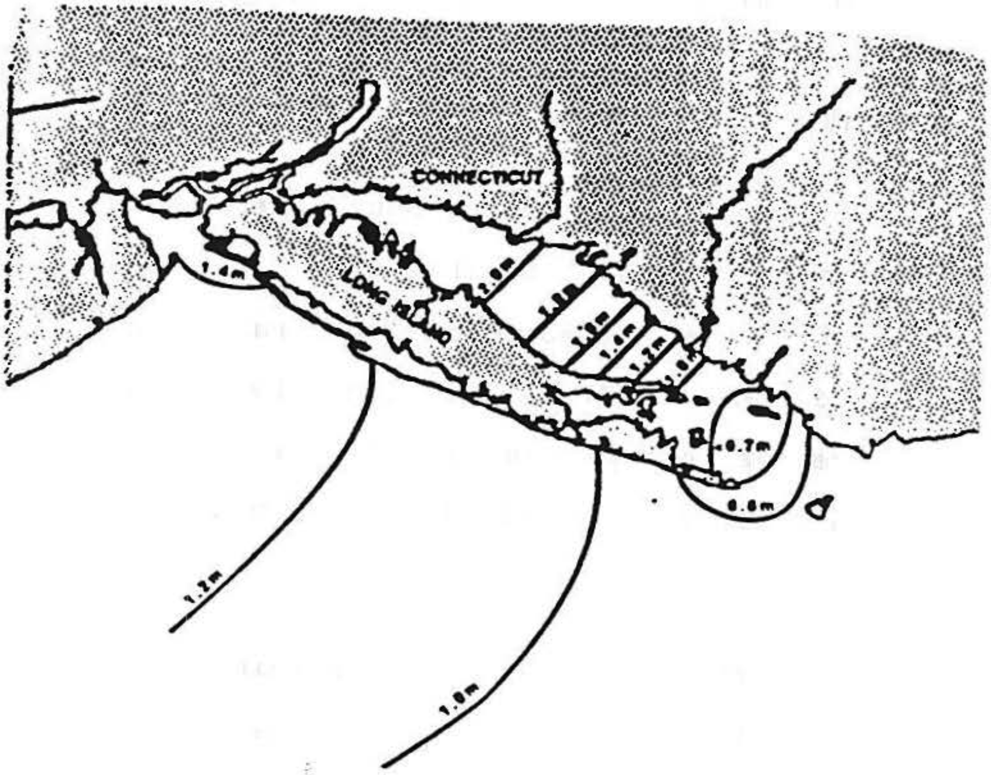


Figure 7. Mean tide range in Long Island Sound and adjacent continental shelf.

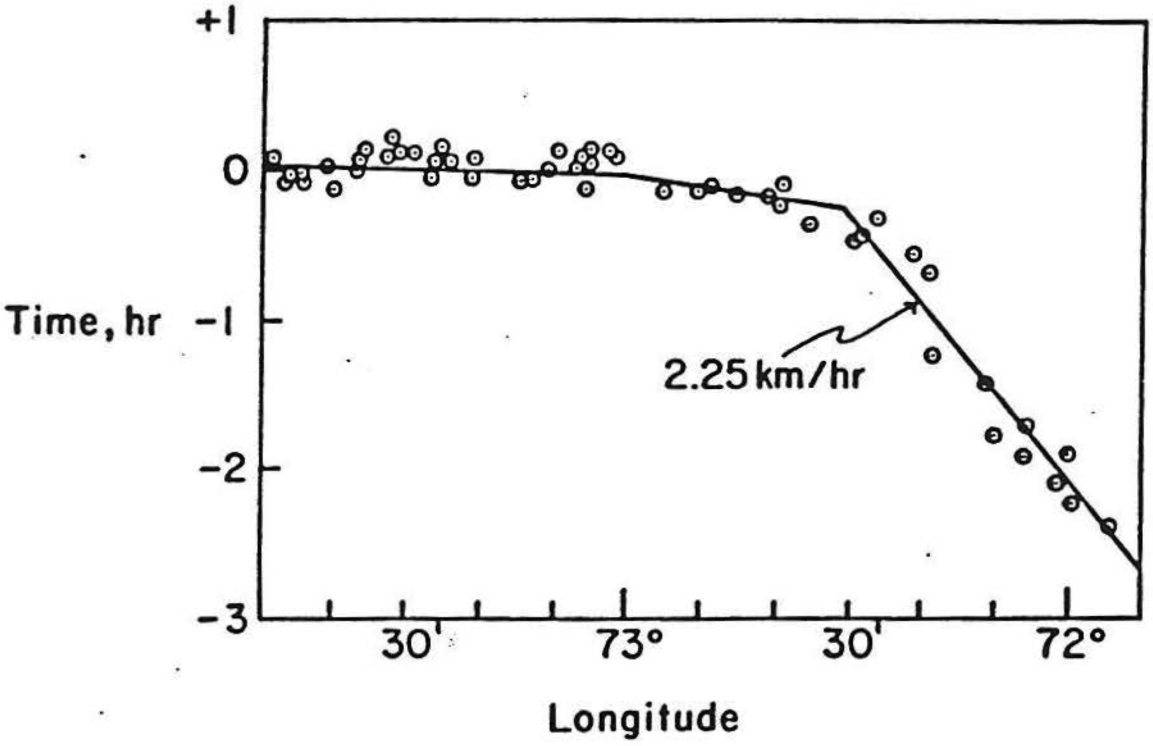


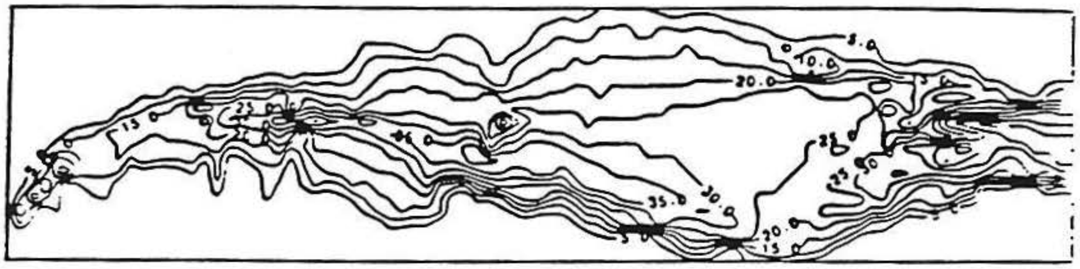
Figure 8. Time of high tide in Long Island Sound relative to Bridgeport, CT as a function of longitude. Abrupt change in slope occurs at Mattituck Sill.

insensitive to the basin length and depth. The morphology of the channel constriction at the mouth becomes the controlling feature of the basin. In particular the Helmholtz period is given by SQRT(LQ/gWH) where Q is the surface area of the basin and H,L,W are the depth, length and width of the channel at the entrance of the basin. The Helmholtz period for the existing bathymetry is approximately 10 hours. Modifications of the bathymetry near Mattituck Sill could alter the Helmoltz period and contribute to a change in existing tidal characteristics of the Sound.

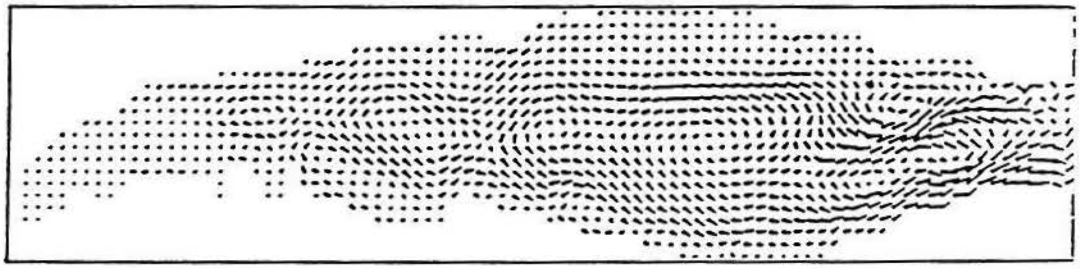
STRATFORD SHOAL

Stratford shoal is an area of relatively intense local tidal mixing. It does, however, exert a more subtle influence on the circulation in the central basin and on the exchange between the western Sound and the central basin.

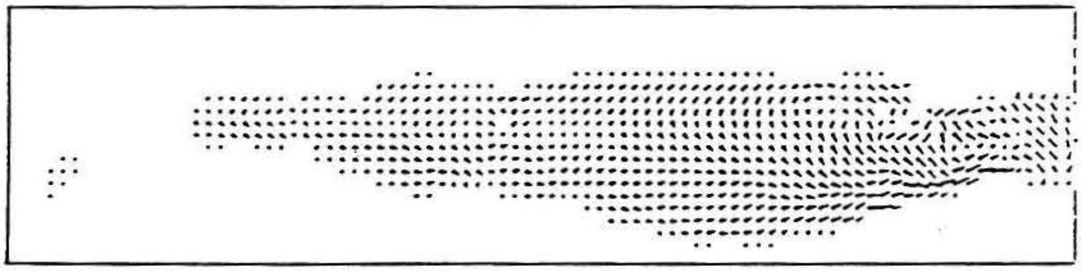
Current observations in the vicinity of Stratford Shoal provide evidence for residual nontidal Eulerian currents of the order 5 cm/s directed laterally across the Sound. Results from numerical simulations (Figure 9) provide insight into the influence of Stratford Shoal on the tidally induced residual currents. The basic pattern is a counterclockwise gyre around the perimeter of the basin. This flow tends to be most intense where bottom slopes are strongest. The bathymetry in the vicinity of the shoal contributes to a short circuiting of this pattern involving appreciable lateral motion. This motion is directed southward to the east of the shoal and northward to the west of the



MODEL DOMAIN AND BATHYMETRY (M)



RESIDUAL HORIZONTAL VELOCITY VECTORS. LEVEL 1
— =10. CM S**-1



RESIDUAL HORIZONTAL VELOCITY VECTORS. LEVEL 2
— =10. CM S**-1

Figure 9. Model domain, bathymetry, and results for horizontal tidally induced residual Eulerian currents in Long Island Sound from two-level barotropic simulations (adapted from Wilson and Vieira, 1991).

shoal. Noteworthy is the fact that this pattern contributes to a recirculation of waters in the western Sound. The pattern of residual Eulerian currents inferred from the relatively comprehensive 1988 NOS/EPA current survey is consistent with this simulated current field (Wilson and Vieira, 1991).

Modification of bathymetry in the vicinity of the shoal could alleviate at least some of this recirculation and lead to enhanced flushing of the western Sound.

EATONS NECK AND LLYOD NECK PROMONTORIES

For this discussion we again refer to Figure 9. Bathymetry associated with LLoyd Neck and especially Eatons Neck contributes to a pair of counter rotating eddies. The clockwise rotating eddy to the east of Eatons Neck merges with the large counterclockwise gyre to the west of Stratford Shoal. The counterclockwise rotating eddy to the west extends across the entire basin and should contribute to appreciable recirculation. These eddy patterns in the western Sound are again consistent with residual Eulerian currents inferred from observations.

Modification of bathymetry in the vicinity of Eatons Neck promontory could alleviate some of the recirculation.

HEMPSTEAD SILL

The Hempstead Sill is a rather broad and poorly defined sill located off Hempstead Harbor. MLW depths over the sill range from approximately 11 to 14 m. Channel depths of 90 m are found to the east and west of the sill. Current observations provide clear evidence for relatively well developed gravitational circulation in the channels on either side of the sill with characteristic velocities of 10 to 15 cm/s at depth. It is likely that the sill represents an impediment to the intrusion of deep water although there is no clear hydrographic evidence for this. Dredging of a channel through the sill should contribute to enhanced deep water intrusion.

EAST RIVER

There is abundant evidence for relatively well developed gravitational circulation within the upper East River with characteristic velocities of the order 10 cm/s (Figure 10). This density induced circulation provides one of the fundamental mechanisms by which low salinity waters are introduced into the western Sound.

The extent to which gravitational circulation is developed with the East River depends on the competing effects of pressure gradient associated with density difference between the ends of the strait and vertical mixing. Very strong tidal mixing within the lower East River and especially in the vicinity of the Hell Gate Sill tends to suppress both stratification and the development of gravitational circulation. Local fresh water input from the Harlem River during flood tide contributes to the

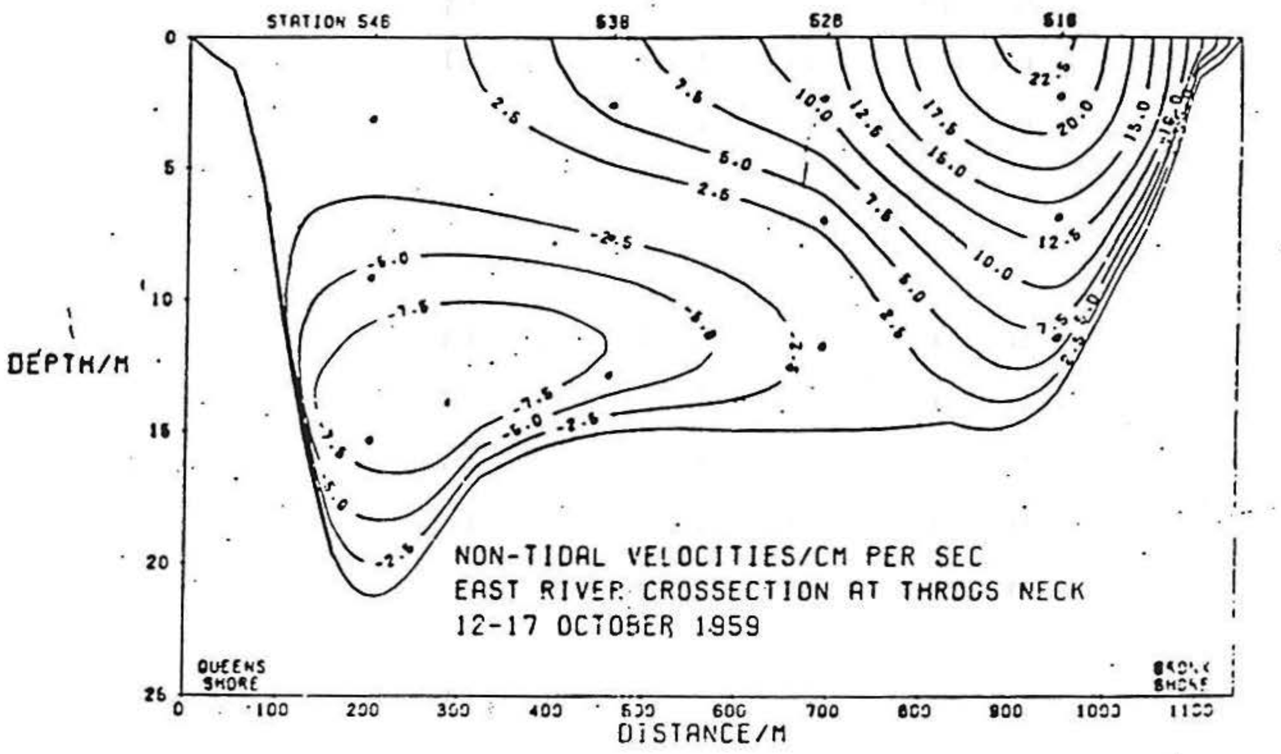


Figure 10. Residual Eulerian currents normal to a section across the East River near Throgs Neck (courtesy M.J. Bowman, unpublished). Positive velocities are directed towards Long Island Sound.

restratification in the upper East River during this phase of the tide.

Filadelfo and Wilson (1991) have shown that there is an appreciable vertical current shear due to gravitational circulation even in the lower East River of the same sign as that in the upper East River. They also showed that the shear throughout the strait exhibits a clear response to fluctuations in Hudson River flow. Salinity structure over a tidal cycle (Figure 11) at stations in both the upper and lower East River shows some tendency for periods of stratification.

A modest increase in channel depth could lead to a significant enhancement in the intensity of gravitational circulation through the strait, especially during neap tides and periods of high river flow or strong surface heating in late summer. This would lead to increased intrusion surface waters into the western Sound, but it would also lead to a possibly desirable enhancement in the movement of deep waters into the East River, with less vertical mixing and recirculation back into the Sound.

HARLEM RIVER

The Harlem River is actually a tidal strait which connects the lower Hudson estuary at Spuyten Duyvil to the East River at Hell Gate. Recent modelling studies of circulation in Long Island Sound conducted by NOAA have emphasized the importance of the

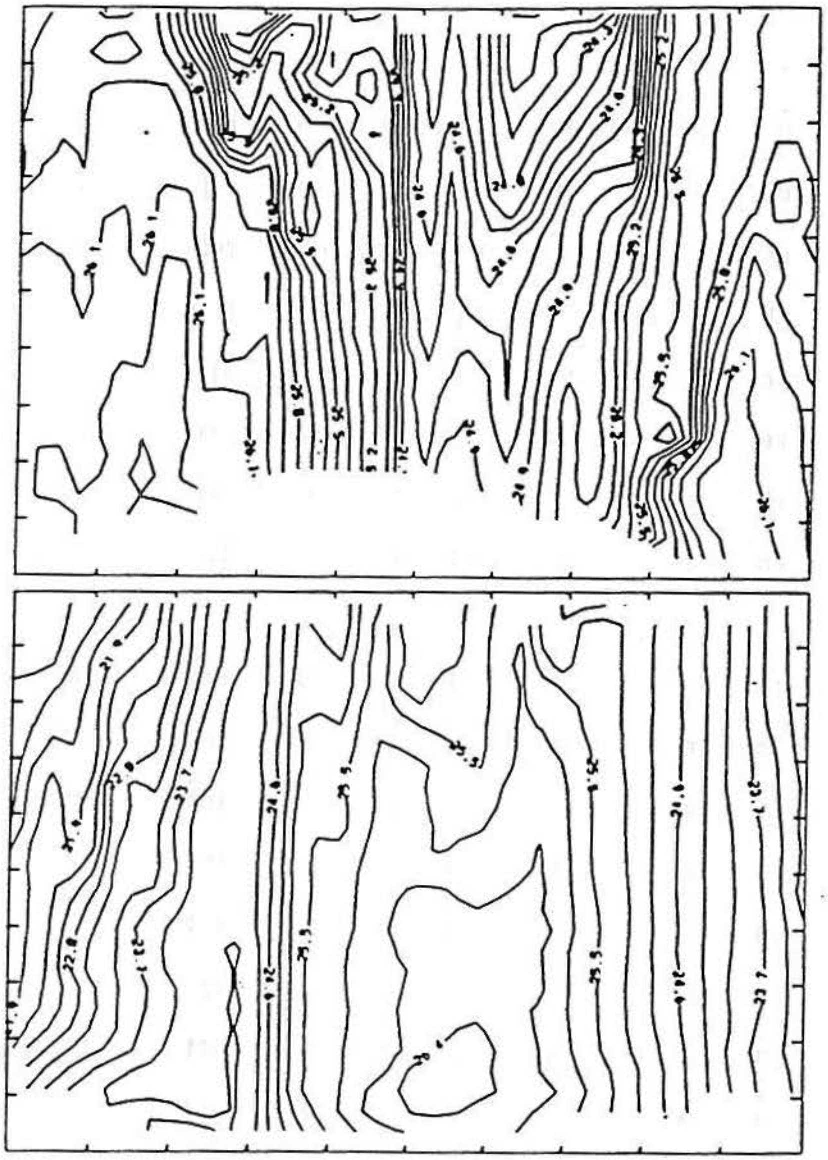


Figure 11. Salinity as a function of depth and time over a semidiurnal cycle in the East River at NOS Station 39 in the upper East River (upper), and NOS Station 33 in the lower East River (lower). Vertical axis is depth 0-25 m. Horizontal axis is time: 0600-1700 on 06/25/59 for Station 39; 0600-1900 on 10/28/59 for Station 33.

Harlem River. The low salinity water it conveys is apparently of considerable importance to the salinity, the stratification, and the residual density induced circulation of both the upper East River and western long Island Sound.

Residual Eulerian and Lagrangian currents in a tidal strait may be produced by nonlinear interactions of the first order tidal motion. The residual currents are strongly dependent on the amplitude and phase differences of the first order tide between the ends of the strait.

Dredging operations near the Hudson River end of the Harlem have contributed to significant changes in the phase of the tide in the upper Harlem. It has also affected the character of the tide and the duration of rise and fall. There has apparently been little effect on range. It appears that channel modifications in this strategically located waterway could have far reaching implications

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Water Conservation Measures and Their Effect on Sewage Treatment and Hypoxia in Long Island Sound

by

R. Lawrence Swanson
Anne Mooney

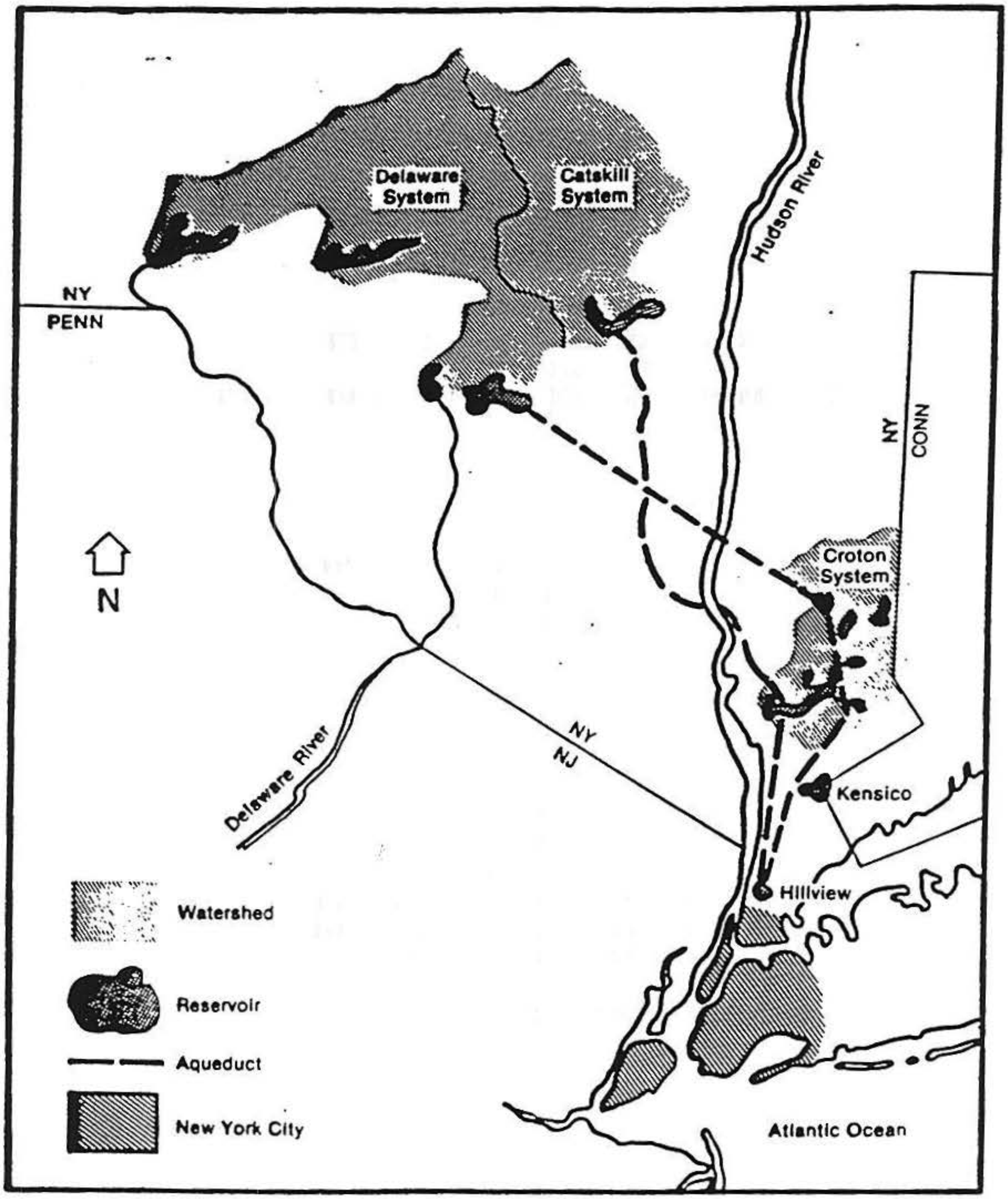
WATER CONSERVATION MEASURES AND THEIR EFFECT ON SEWAGE TREATMENT AND HYPOXIA IN LONG ISLAND SOUND

A White Paper
Presented to the U.S. Environmental Protection Agency
Region 1
Boston, MA

by

R. Lawrence Swanson
and
Anne Mooney
Marine Sciences Research Center
State University of New York
Stony Brook, NY

November 6, 1991



New York City water supply system. After Gunnerson, 1981.

Introduction

It is generally accepted that low levels of dissolved oxygen (DO) in the bottom waters of Western Long Island Sound (WLIS) are due to excessive nutrient loads. Data from the Long Island Sound Study (LISS, 1990) have shown that the collapse of algal blooms is linked to nitrogen depletion; in other words nitrogen is the limiting nutrient. Wastewater treatment plants in New York City are among the principle sources of nitrogen and other nutrients. Surface runoff, river discharge, and sewage effluent from other sewage treatment plants surrounding Long Island Sound also contribute significantly to the eutrophication of the Sound. Sources of nitrogen to the Sound, according to LISS (1990), are as follows: 37% enters across the boundaries of the Sound at the Race and via the East River, 28% is from point sources (mainly sewage treatment plants) discharging directly to the Sound or in its coastal zone; 23% is from river discharge; 8% is from atmospheric deposition; and 5% is from coastal runoff including combined sewer overflows (CSOs).

The composition of nitrogen in sewage effluent changes when the detention time of the waste water in treatment plants increases. As the detention time increases, a greater proportion of total nitrogen is in the form of nitrate (NO_3) and a lesser proportion is in the form of ammonium (NH_4). The release of higher percentages of nitrate to receiving waters is preferable for two reasons: 1) the nitrogen is already in its most oxidized form; and 2) studies have shown that phytoplankton may preferentially take up ammonia over nitrate (Carpenter, 1985). The effect of releasing nitrogen in the form of nitrate may result in the delay of its uptake by phytoplankton, thereby allowing the nitrogen to disperse more widely before it is consumed by algae. If New York City can reduce the flow to its sewage treatment plants through water conservation efforts, then the average detention time could be increased and a higher percentage of the nitrogenous wastes will be in the form of nitrate.

Cities around the country have recognized the need to reduce their rates of water consumption as a result of either severe and persistent drought conditions or to long term demand outstripping their ability to supply water. A number of residential water conservation programs implemented by cities around the country are reviewed in a report funded by the U.S. Department of Housing and Urban Development (HUD) entitled "Residential Water Conservation Projects, Summary Report." These efforts include: 1) requirements that low-flow fixtures be used in all new housing; 2) retrofitting of plumbing in existing homes; 3) metering in areas previously billed on a flat rate basis; and 4) reductions in water main pressure. In addition, some areas have made an effort to reuse "greywater," which is essentially residential water other than toilet water.

It is useful to review whether these conservation measures would have any impact on the New York City sewage treatment plant system and in particular the hypoxia problem in WLIS. At the present time, New York City consumes approximately 1424 million gallons per day (MGD) and treats some 1770 MGD of sewage (Fig. 1). Water usage for commercial and residential purposes amounts to about 200 gallons per capita per day (GCD) (Fig. 2), which is certainly at the upper limit of cities around the world (Gunnerson, 1991). However, extravagant usage requires extensive and expensive treatment and Gunnerson (1991) points out that at the upper limits of usage, the ratio of costs of treatment to supply can be as large as 15 to 1. These costs do not include any of the environmental costs associated with the impact treated effluent may have on receiving waters.

Water Conservation Measures

Low-flow Fixtures

New York State amended the Environmental Conservation Law (Chapter 424, Laws of 1989), which requires the use of low-flow fixtures in all new housing (effective January 1, 1991). The ammendment reduces the maximum flow rate for lavatory faucets from 3 to 2 gallons per minute (GPM); sets a maximum flow rate for shower heads (at constant pressure of 60 psi) of 3 GPM; and reduces the maximum flow standard for "water closets" from 3.5 gallons of water per flush to an average of 1.6 gallons per flush. The maximum flow standard for sink faucets is retained at 3 GPM. The bill also requires the use of self-closing faucets and drinking fountain valves in all public buildings. The savings in water use are difficult to gauge. It is useful to compare these requirements with similar programs.

In a nation-wide study on residential water conservation projects funded by U.S. HUD (HUD, 1984), the savings gained from using low-flow fixtures were as follows:

- Low-flow shower heads (3 GPM) saved 7.2 GCD. The difference in the amount of energy required to heat the water used in showering amounted to a savings of about $8 per person for gas heated water and about $26 per person for electric heating annually, using typical 1983 energy prices.
- Low-flush toilets (3.5 gallons per flush) saved 8.0 GCD compared to a 5.5 gallons per flush toilet, and based on an average of four flushes per person per day. Based on the same calculations, if the New York State standard of 1.6 gallons per flush is compared to the conventional 5.5 gallons per flush toilet, the savings are 15.6 GCD.
- Water efficient clothes washers save about 1.7 GCD.
- New conserving dishwashers save about 1.0 GCD.

The authors of the study note that the total water saved by switching to low-flow fixtures in single family homes is less than predicted because many homeowners had already retrofitted fixtures in their homes. They suggest that savings of 13.0 GCD in single family homes and 16.3 GCD in multi-family homes are more typical.

Total savings would amount to approximately 22.8 GCD if New York State's standard for toilets is used (with a savings of 15.6

GCD) and the HUD figure for low-flow showers is used (which amounts to a savings of 7.2 GCD), and ignoring possible gains from switching to more efficient dishwashers and washing machines. If this is multiplied by New York City's population of 7 million people, the potential savings is 160 MGD -- a significant amount.

Using HUD's estimate for typical savings in multi-family homes of 16.3 GCD (which is based on toilets that use 3.5 rather than 1.6 gallons/flush) and multiplied that by 7 million people, the savings would equal 114 mgd.

These calculations do not factor in the effect of reducing maximum flow rates on lavatory faucets from 3 to 2 GPM or the requirements regarding self closing valves on public drinking fountains and lavatories, which are also mandated in the recently published New York State regulations.

Savings from low-flow fixtures will probably not be fully realized for at least another 30 years or so given that the "life expectancy" of conventional fixtures is about 30 years.

Retrofitting

Retrofitting programs are aimed at existing housing and usually involve the distribution of free retrofit kits. The kits usually include shower flow restrictors (3 GPM), toilet tank displacement devices (which save 0.5 to 0.7 gallons per flush), and leak detection tablets. The HUD report (1984) reviews the effectiveness of four retrofit programs in California and one in Washington, DC. The programs in California were conducted by the

Los Angeles Department of Water and Power (LADWP), the East Bay Municipal Utility District (EBMUD), the North Marin County Water District (NMCWD), and the North Tahoe Public Utility District (NTPUD). The LADWP and the EBMUD programs were conducted in 1981 under normal conditions, and the NMCWD of the NTPUD programs were conducted during drought conditions from 1976 to 1977.

The LADWP used a bulk mailing to distribute 1.2 million kits following an intensive public promotion campaign. Several months later a brief questionnaire on postcards was sent out to ascertain how many people had installed the devices. They found that 27% of the toilet tank bags and 21% of the shower flow restrictors had been installed. Later they found that these figures had dropped to 19% and 10% respectively. For those who installed the devices, water savings amounted to 6.7 GCD. For the utility companies this amounted to annual savings of approximately 1.2 billion gallons.

In Lake Tahoe, where the installation of retrofitting devices was required by town ordinance during a severe drought, installation rates were nearly 100% for all multiple dwellings (including hotels) and about 80% for single family homes. The utility conducted a follow-up survey five years later and found that the installation rate for toilet dams had dropped to about 48% and to about 64% for the shower restrictors.

In Washington, D.C., with similar climate and social conditions to those of New York City, 23 apartment buildings were retrofitted. The retrofit usually involved the installation of low-flow shower heads, toilet tank displacement devices (toilet dams), and faucet aerators. The three-year average water use after the retrofit was approximately 84 GCD. This usage is about the same as the usage in new nonretrofitted garden apartments of 83 GCD. Reductions per unit ranged from 3 to 117 gallons per day (GPD) and averaged 60 GPD (or 30 GCD). Table 1 shows water use before and after retrofitting. Almost all of the buildings had leaking toilets which were fixed by installing new flapper valves and ballcocks. Savings due to fixing leaking toilets amounted to 24 gallons per day per toilet (about 24 GCD). Assuming that leaking toilets are as widespread in New York City as in Washington, D.C., savings due to retrofitting and toilet repair could amount to as much as 210 MGD (30 GCD x 7 million people).

The estimates of savings due to retrofitting and switching to low-flow fixtures should not be added together but viewed as alternative potential savings. Therefore the savings due to retrofitting have not been included in table 3. It should be noted, however, that the estimated savings obtained by switching to low-flow fixtures is based on a reduction in usage from 5.5 to 1.6 gallons per flush and does not take into account that many of the older fixtures may be leaking. The total savings listed in table 3 may therefore be an underestimation of the full potential savings.

New York City requires building owners to install flow restrictors on shower heads and faucets under emergency drought conditions but savings due to these requirements are not available.

Metering

New York City initiated its "Universal Metering" program in 1986. The installation of meters actually began in 1988, and is scheduled to finish in 1998. The City plans to meter all single, two, and three family houses. Larger apartment buildings will have one master meter for the whole building. Commercial and industrial buildings have always been metered in the City.

Prior to the initiation of the program, building owners were billed according to a flat rate based on land area. Universal metering will tie billing to consumption, which should result in significant savings and greatly enhance the ability of the New York City Bureau of Water Supply to monitor demand.

The HUD (1984) report cites studies which showed reductions in water consumption ranging from 22-45% in several cities that had switched from flat-rate to metered systems. However, the authors point out that these studies must be viewed carefully. Most are based on city-wide or district-wide comparisons of metered and unmetered water users including commercial and industrial users. Other reports showed only initial reductions in water use following metering of flat-rate systems.

HUD conducted a three-year study in Denver, CO on the effects of metering on water consumption designed to avoid these comparison difficulties (HUD, 1984). This study focused on three adjacent neighborhoods selected for their demographic, socioeconomic and physical similarities. Forty-two houses were included in the study, 25 of which were metered. HUD found that metering reduces total consumption by about 20%. However, the authors assert that "the principle effect of metering is to reduce the amount of water used for landscape irrigation...water use during the winter, when landscape irrigation is minimal, is very similar for metered and flat-rate homes"(Fig. 3). Since outdoor water use is presumably a much smaller percentage of total consumption in New York City than it is in Denver, metering may result in a smaller reduction in water use. We estimate 10% or so may be more reasonable. However, Metcalf and Eddy (1991) point out that "The waste and unaccounted-for water in metered systems ranges from 10 to 20% of the total water entering the distribution system. The corresponding range in unmetered systems is much higher (typically 30%)."

By improving the monitoring of water use, New York City may be able to more effectively reduce the amount of waste. A Hazen and Sawyer Study of Water Demand in New York City estimated "system leakage" at about 133 MGD in 1985 (Table 2). If usage in "vacant lots" (17 MGD), "abandoned buildings" (22.5 MGD), and a "miscellaneous" category (25.6 MGD) were added together with "leakage," waste makes up almost 13% of the total flow (1,515 MGD). (This figure for total flow is for 1985 and includes water from the Jamaica Water Supply Company wells, whereas the figure of 1424 MGD cited on the previous page is the average total flow in 1990 from New York City supplies).

Effect of Water Pressure on Usage

The HUD report (1984) sites several studies on the effect of reducing pressure in water mains on water usage. These include areas in Denver, Los Angeles, and Atlanta. They found that reduction in pressure of 30 to 40 psi could lead to a savings of about 6%. The savings would come primarily through a reduction in water system and house plumbing leakage. However, they point out that it is probably not practical to reduce water pressure in existing developed areas. Limiting pressure in new developments to 50 or 60 psi may save water and energy from the lower water system pumping head requirement.

Reuse of Greywater:

During the 1991 Legislative Session a new law (Chapter 180, Laws of 1991) was enacted regarding the reuse of greywater. The Act requires the New York State Department of Environmental Conservation (NYDEC), in consultation with the New York State Department of Health (NYDOH), to establish rules and regulations for the reuse of greywater. The law is intended to allow and encourage the use of greywater in order to reduce the use of potable water. The concept of reusing greywater for toilet flushing and landscape irrigation probably has little application for residential housing in New York City but may have potential for the surrounding suburbs.

In Tuscon,AZ, where groundwater is being depleted at a rate of 250,000 acre-feet per year, an experimental house called "Casa del Agua" was designed and retrofitted to low water use fixtures and water reuse systems. All greywater from the washing machine, tub, shower, lavatories, and one side of the kitchen sink is directed into a collection sump on the south side of the house. A small sump pump is activated at a selected water level. The collected greywater then enters the first of two galvanized 300 gallon horse tanks (aquacells). Water hyacinth plants floating on the surface of these aquacells are used to treat the greywater. The treated greywater overflows into a sandfilter and is then directed to a storage tank. This water is used for landscape irrigation and toilet flushing.

The house relies on three sources of supply: municipal ground water (37 GCD, 47%), rainwater (12 GCD, 15%) and greywater (30 GCD, 38%). The rainwater is used primarily for an evaporative cooling system. A gutter system designed to capture runoff from the roof and a separate storage tank are reserved for this system.

Through the use of greywater, captured rainwater, advanced low-flow toilets (1.0 gallon per flush) and other water conserving fixtures, and low water landscaping, "Casa del Aqua" uses about 47% of the municipal groundwater used in "typical" Tuscon homes.

Discussion

Some of the programs outlined above may result in substantial reductions in water consumption for New York City (Table 3). The study by Hazen and Sawyer estimates projected savings due to programs the City is currently pursuing: water metering, conversion to low-flow fixtures, and repair of leaks in water mains (Table 4).

With reductions in per capita demand, the authors of the Hazen and Sawyer study estimate that total water consumption will remain fairly constant over the next 40 years or so. The financial savings to the City could be substantial. David Ho, an economist with the New York City Department of Environmental Protection (NYCDEP) is currently working on an estimate, which may be ready this winter.

Water conservation would also reduce the need to pump water from the Hudson River, which the City has occasionally had to do when reservoir levels are low. In the past 25 years the city has pumped water from the Hudson River three times:

May 21, 1966 - January 13, 1967
July 10, 1985 - December 11, 1985
May 1, 1989 - May 16, 1989

There has also been test pumping at the Chelsea pumping station but amounts of water withdrawal were relatively insignificant (Anne Seeley, NYDEP, personal communication).

Water withdrawals from the Hudson River are of concern for two reasons: pumping river water requires some additional level of treatment; and water withdrawals from the Hudson could reduce the fresh water required to drive the two layer estuarine circulation in WLIS. Under normal conditions the surface waters, which are lower in salinity, flow from the East River into WLIS while bottom waters flow in a westerly direction towards the New York - New Jersey Harbor bringing more oxygenated waters from Eastern Long Island Sound.

In one instance, water reductions have proved to result in some negative effects on sewage treatment. In 1976-77 when faced with a severe drought, Marin County, CA, instituted a variety of conservation measures including: a tiered rate system, a very successful retrofit program, and reuse of greywater. Through these efforts and a public appreciation of the severity of the drought, water consumption dropped from 120 GCD to 33 GCD (Romm, 1981). Decreased flows through the sewage system resulted in higher sedimentation, hydrogen sulfide generation, and clogging in sewers. It is considered highly unlikely that conservation efforts would reduce waste water flow to the point where it becomes a problem for the treatment plants in New York City (Jackie Sartoris, NYCDEP). New York City has a very dilute sewage.

Conclusion

Water conservation measures could reduce consumption, and consequently the volume of sewage needing treatment, by approximately 390 MGD (Table 3). This is a reduction of about one-quarter of the present volume, and roughly equivalent to the volume treated by one of New York City's largest sewage treatment plants. If one assumes that an increase in demand due to population growth will negate reductions in consumption that would otherwise be achieved through conservation, as is the case with the Hazen and Sawyer projections (Table 4), then the city would at least save the expenses associated with the construction and maintenance of an additional sewage treatment plant. Alternatively, if one assumes that New York City's population will remain constant, as it has over the past 20 years, then the reduction in waste water could be used to improve treatment. One such measure could be to increase detention times in the treatment plants for the purpose of converting ammonium to nitrate -- a process that may have a measurable impact on oxygen demand in the receiving waters.

Figure 1

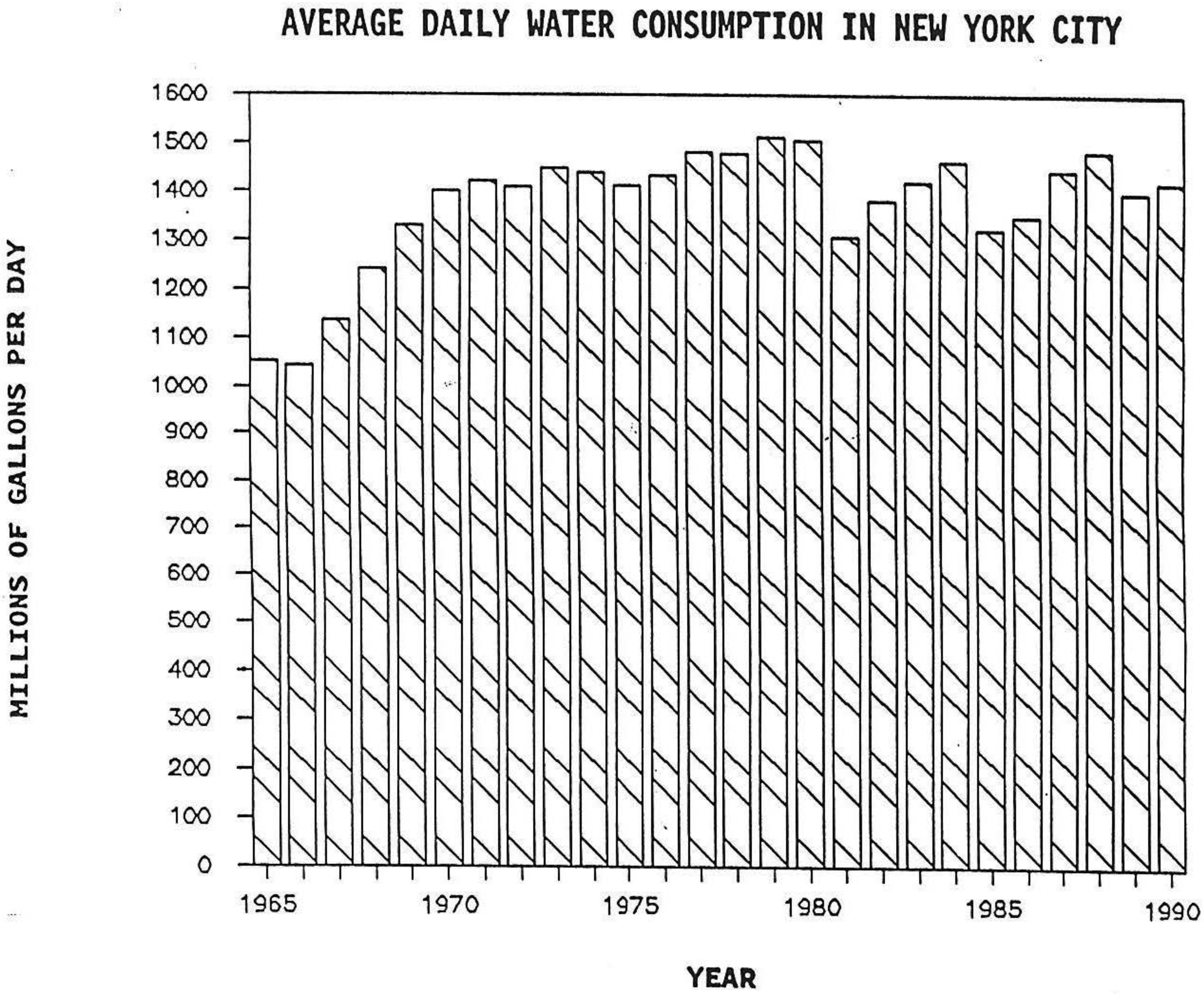
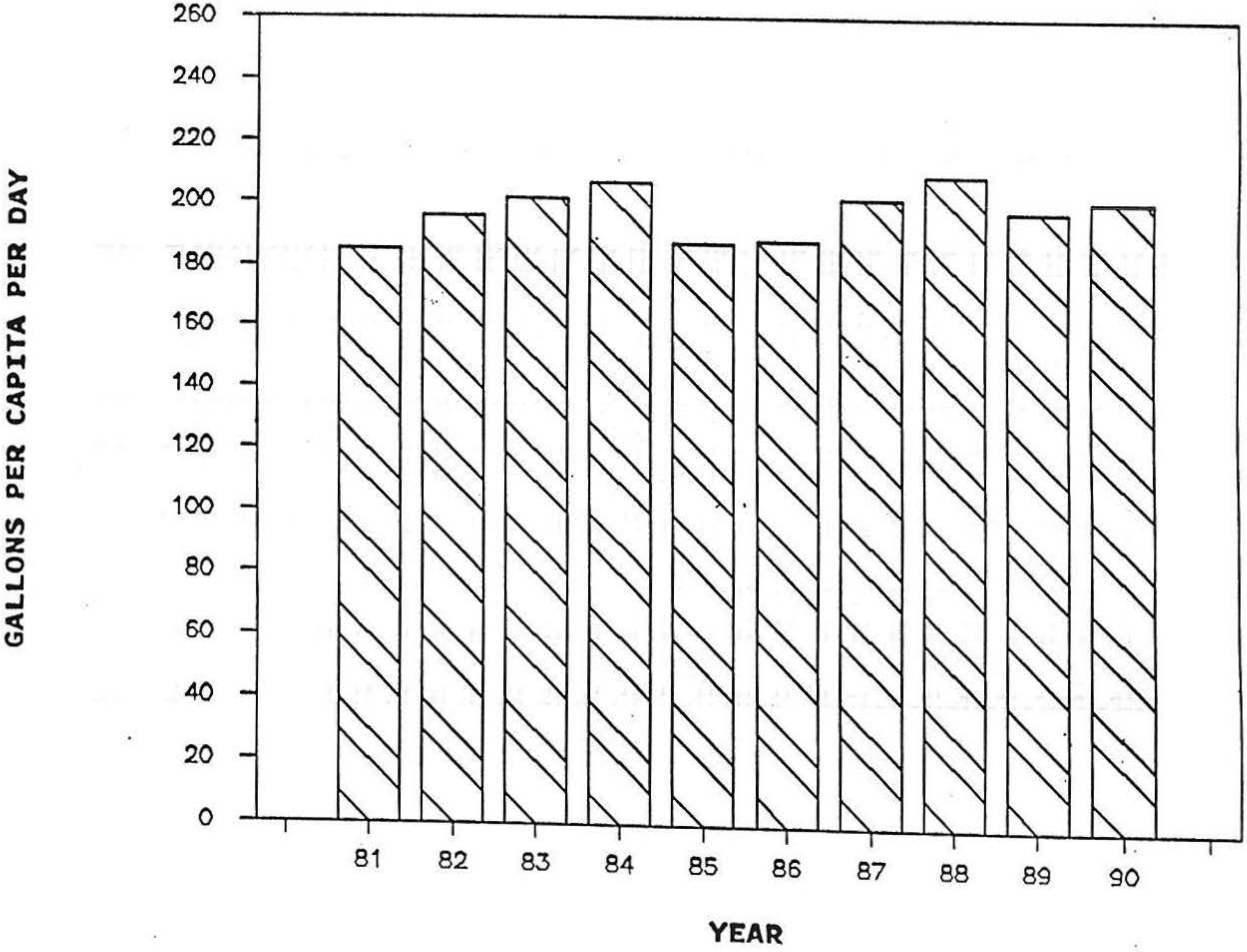

AVERAGE DAILY WATER CONSUMPTION IN NEW YORK CITY
MILLIONS OF GALLONS PER DAY
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
1965
1970
1975
1980
1985
1990
YEAR

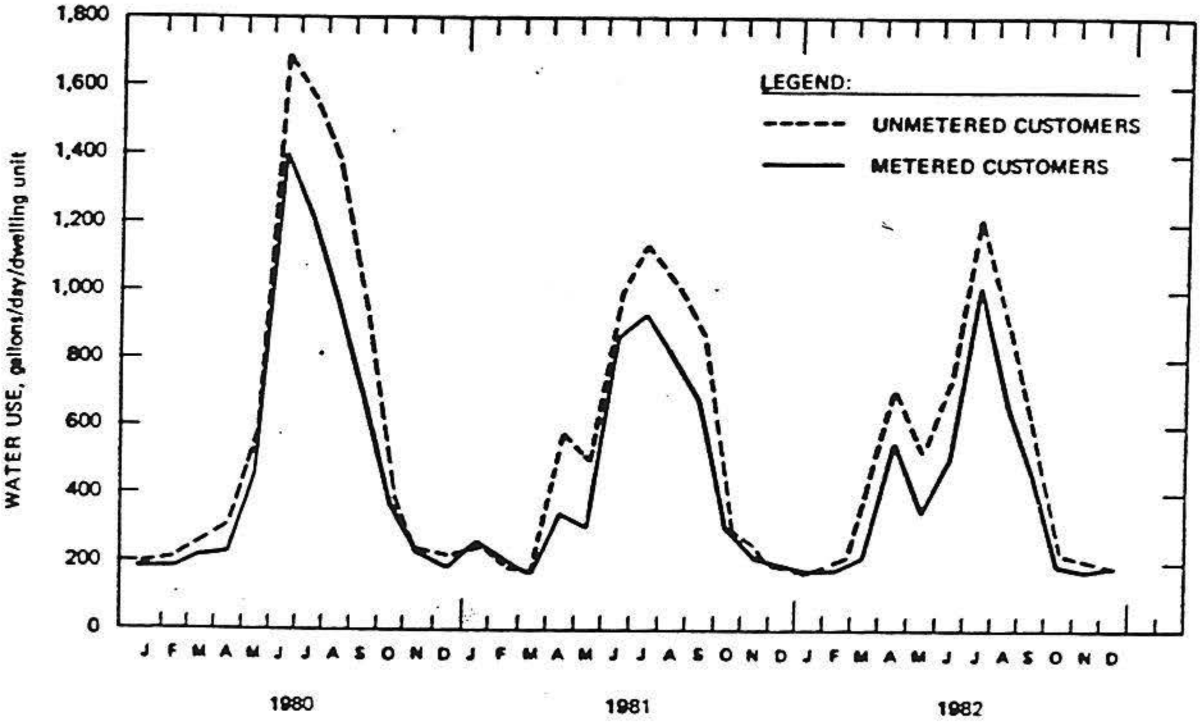
Figure 2

DAILY PER CAPITA WATER CONSUMPTION IN NEW YORK CITY



footnote: includes commercial and industrial

Figure 3: Average Daily Water Use -- Denver Metering Study



From: HUD, 1984.

Table 1

Comparison of Water Use in Buildings Retrofitted After 1981--Washington, D.C., Area

Building type	Name	Number of units	Date retrofitted	Before retrofit January-February 1981		After retrofit January-February 1983		Savings, gpd/unit
				gpd/unit	gcd	gpd/unit	gcd	
High rise	Skyline Plaza	936	September 1980	170[a]	94	123	68	47
	Watergate I	400	January 1981	180	90	139	70	41
	Watergate II	400	January 1981	190	95	138	69	52
	Watergate III	400	February 1981	186	93	138	69	48
Garden	Portabello	254	July 1981	261	104	163	65	98
	Londonderry	529	August 1981	206	94	170	71	36
High rise	The Willoughby	811	January 1982	192	66	189	65	3
	Cavalier Club	220	November 1981	247	154	130	81	117
Garden	Fountain Park	156	February 1982	250	76	150[b]	45	100
High rise	Triangle Towers	260	July 1982	235	157	141	94	94
Garden	Lakeside North	278	September 1982	178	77	164	71	14
Average		-		209	100	149	70	60

[a] Data from January-February 1980.

[b] Meter was malfunctioning during January through February.

From: HUD, 1984

Table 2: Forecast of New York City Water Use

YEAR	1985	1995	2005	2015	2025	2035
NEW YORK CITY WATER USE SECTOR	BASE YEAR WATER USE, MGD	FORECAST WATER USE ,MGD				
A. RESIDENTIAL USE						
1. One Family	117.668	108.00	115.39	122.61	129.87	137.18
2. Two Family	130.144	114.79	118.76	122.48	126.24	130.05
3. Condominiums & Co-Ops	119.080	120.87	122.93	124.30	125.33	126.02
4. Tenement	290.097	288.94	288.82	287.20	284.97	282.14
5. All Other multi-family	303.569	303.67	304.79	304.35	303.24	301.48
Subtotal	960.558	936.27	950.69	960.94	969.64	976.87
B. NON-RESIDENTIAL USE						
6. Construction	6.562	7.92	8.07	8.21	8.36	8.50
7. Manufacturing	63.215	48.11	45.00	41.99	39.07	36.25
8. All Transportation	13.840	12.64	12.81	12.98	13.13	13.27
9. Communications	1.466	1.30	1.22	1.15	1.08	1.01
10.Utilities and Sanitary services	5.201	4.53	4.50	4.47	4.44	4.40
11.Wholesale Trade	51.368	53.90	55.76	57.62	59.49	61.36
12.Retail Trade	64.301	67.75	70.02	72.30	74.59	76.89
13.Finance, Insurance & Real Estate	13.661	15.16	15.12	15.07	15.02	14.96
14.Health Services	21.284	25.69	26.70	27.72	28.77	29.83
15.Educational Services	12.334	14.60	14.85	15.10	15.35	15.60
16.Other Services	29.320	36.06	37.08	38.11	39.15	40.19
17a.Public Administration	14.479	14.28	13.79	13.29	12.79	12.28
17b.Public Parks	34.321	34.32	34.32	34.32	34.32	34.32
17c.Bronx Zoo, Brooklyn Aquarium	23.000	22.31	21.64	20.99	20.36	19.75
17d.Bronx Botanical Gardens	2.000	1.94	1.88	1.83	1.77	1.72
Subtotal	356.353	360.51	362.77	365.16	367.68	370.34
C. OTHER USE						
18.Fire	0.463	0.47	0.47	0.48	0.48	0.49
19.System Leakage	132.934	94.02	86.14	81.33	76.48	71.58
20.Vacant Lots	17.010	14.03	14.03	14.03	14.03	14.03
21.Abandoned Buildings	22.460	18.53	18.53	18.53	18.53	18.53
22.Miscellaneous	25.641	21.15	21.15	21.15	21.15	21.15
Subtotal	198.508	148.21	140.33	135.52	130.68	125.78
Total	1,515.419	1,445.0	1,453.8	1,461.6	1,468.0	1,473.0
Supplied by JWSC Wells	43.900	20.000	0	0	0	0
Total from New York City System	1471.519	1,425.0	1,453.8	1,461.6	1,468.0	1,473.0

From: Hazen and Sawver

Table 3

Estimated Savings due to Conservation Measures:

1) Low-flow fixtures	140 MGD
2) Metering	100 MGD
3) Repair of water main leaks	150 MGD
Total	390 MGD

Notes: 1) 140 MGD is an intermediate figure between 114-160 MGD savings - see text. This figure will vary depending on the assumptions about the type of fixtures currently in use. The amount of leakage from those fixtures is not included in this figure.

2) this figure is based on a 10% reduction in residential use which is about 65% of total consumption (.65 x 1500 mgd x 10%)

3) assumes savings due to repairs is about 10% of total flow.

Table 4: Effects of Conservation Measures on Demand in New York City.

	NYC Demand - Met By NYC Sources				
	1995*	2005	2015	2025	2035
Projected Demand Without Conservation	1611.3	1739.1	1845.1	1952.6	2061.4
Savings Due to Conservation Measures					
o Reduced Use Due To Initial Conversion Of Flat Rate Accounts	35.0	35.0	35.0	35.0	35.0
o Reduced Use Due To Price Increases	48.5	76.6	104.6	133.4	163.0
o Reduced Use Due To Replacing Plumbing Fixtures	33.6	69.8	106.5	143.6	181.1
o Reduced Use Due To Multi-Family Residential Conservation	23.4	50.2	78.9	109.2	141.0
o Savings Due To Improved Programs Dealing With Leakage, Abandoned Buildings and Vacant Lots	45.8	53.7	58.5	63.4	68.3
Savings Sub-Total	186.3	285.3	383.5	484.6	588.4
Projected Demand With Conservation	1425.0	1453.8	1461.6	1468.0	1473.0

* In 1995, total New York City Demand Without Conservation is projected to be 1631.3 mgd of which 20.0 mgd is assumed to be met by Jamaica Water Supply Company wells. Total projected demand with conservation is 1445.0 mgd.

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Structures to Reduce or Eliminate Hypoxia in Western Long Island Sound

by

Malcolm J. Bowman

STRUCTURES TO REDUCE OR ELIMINATE HYPOXIA IN WESTERN LONG ISLAND SOUND

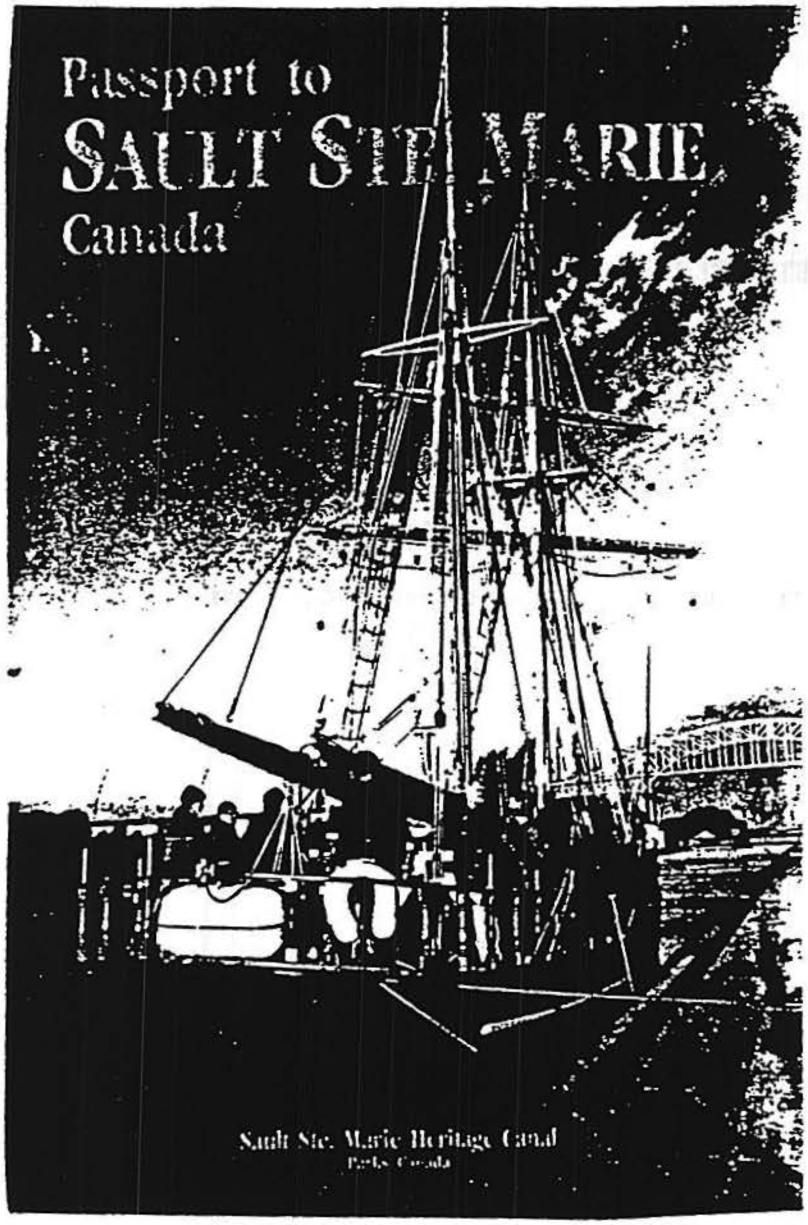
A White Paper

presented to the US Environmental Protection Agency
Region I
Boston MA

by

Malcolm J. Bowman
Marine Sciences Research Center
State University of New York
Stony Brook NY 11794

4 November 1991



Frontispiece: Schooner waiting inside the Soo Lock, Sault Sainte Marie, MI and Ontario.

TABLE OF CONTENTS

I. INTRODUCTION..1

Why is There a Serious Hypoxia Problem in Long Island Sound?.....1

II. REGIONAL TIDAL CIRCULATION AND ASSOCIATED VERTICAL MIXING.......3

III. FIXED STRUCTURES AND TIMED RELEASES OF SEWAGE TO ALLEVIATE HYPOXIA IN WESTERN LONG ISLAND SOUND...........................4

Vertical Stirring Poles...4

"Dutch Doors" across the East River.............................5

Timed Sewage Releases...5

IV. TIDAL LOCKS TO ELIMINATE HYPOXIA...............................6

V: EXPECTED IMPROVEMENTS IN WATER QUALITY..........................9

VI. ENGINEERING AND CONSTRUCTION ASPECTS..........................11

VII: OPERATIONAL ASPECTS..12

Navigation through the Locks...................................12

Operation and Maintenance Considerations.......................13

XIII: SIDE EFFECTS...14

Potential Navigation Delays and/or Congestion..................14

Effects on Tides and Currents in the Region....................15

Increased Salinity in Long Island Sound and New York Harbor.....15

Increased Sewage Loadings to the Bight.........................16

IX: OTHER LOCK/BARRIER SYSTEMS WE CAN LEARN FROM...................17

X: WHAT FURTHER SCIENTIFIC RESEARCH IS NEEDED?.....................17

XI: REFERENCES...19

I: INTRODUCTION

Why is There a Serious Hypoxia Problem in Long Island Sound?

There are many factors contributing to the serious water quality problems experienced in New York Harbor, the Hudson River and western Long Island Sound. High on the list is the immense volume of sewage effluent discharged from an estimated 17 million people, representing about 8% of the population of the United States. These people live crowded around the narrow and poorly flushed waterways, rivers and estuaries of New York City, the lower Hudson River, northern New Jersey, NY and CT counties along the north shore of the western Sound, and western Long Island (Fig. 1). Over 90 $m^3 s^{-1}$ (2.1 billion gallons per day) of treated and untreated effluent are continuously released into the waters surrounding the City (Suszkowski, 1973). Of this total, 24 $m^3 s^{-1}$ (560 million gallons per day) are released directly into the East River (region 1 in Fig. 2) from four of the largest sewage works in the city (Wards Island, Bowery Bay, Hunts Point, and Tallmans Island; Fig. 1).

In addition another 6 $m^3 s^{-1}$ (140 million gallons per day) are released from local communities directly into western Long Island Sound (regions 2-4 in Fig. 3).

The sewage effluent released by New York City into its waterways exceeds the mean summer freshwater discharge of the Hudson River.

The problem of combined storm and municipal waste sewer systems in New York City remains critical even in the light of massive construction of sewage treatment facilities; "... The money spent for this construction in large part will be wasted if means of mitigating the effects of combined sewers are not found" (Interstate Sanitation Commission, 1972). The situation has not improved much since then.

It has been estimated that approximately 15 $m^3 s^{-1}$ (400 million gallons per day) of New York City's discharge are transported by tidal dispersion into western

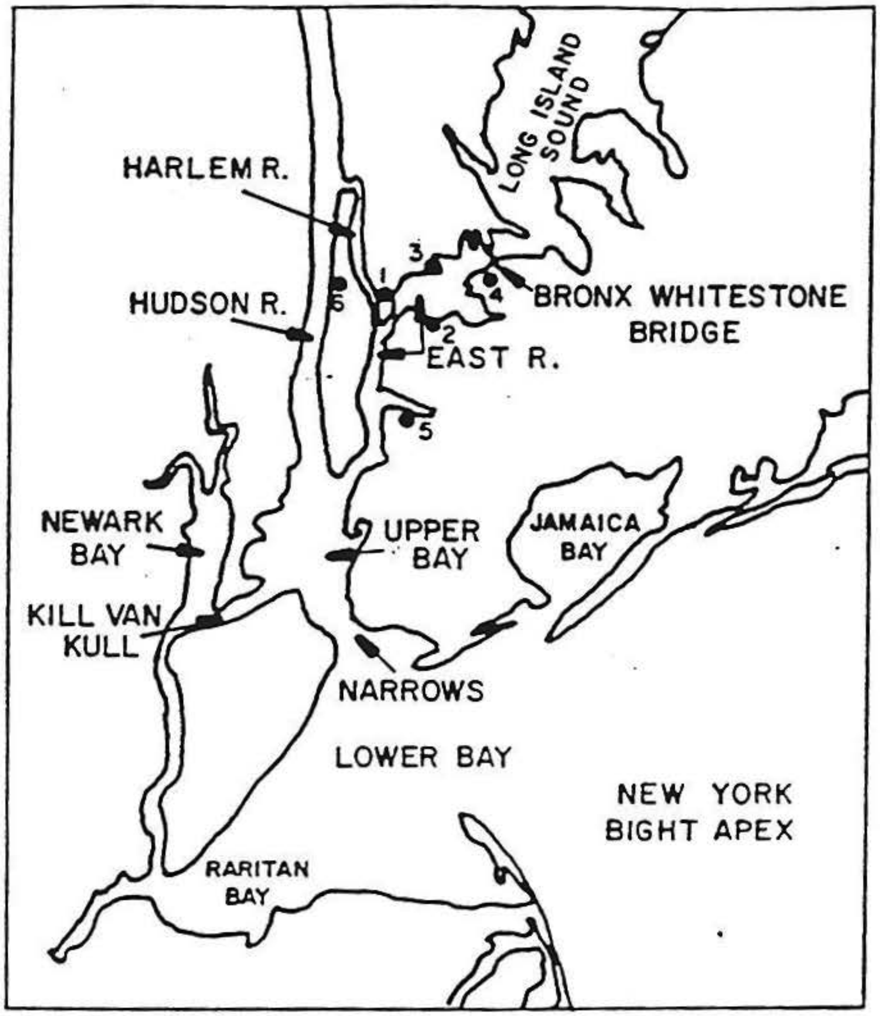


Fig. 1: Locator map of greater New York Harbor. There are 76 sewage treatment plants located within the area shown. Six of the major plants around the East and Hudson Rivers are: 1-Wards Island; 2-Bowery Bay; 3-Hunts Point; 4-Tallman Island; 5-Newtown Creek; 6-North River (from Bowman, 1976d).

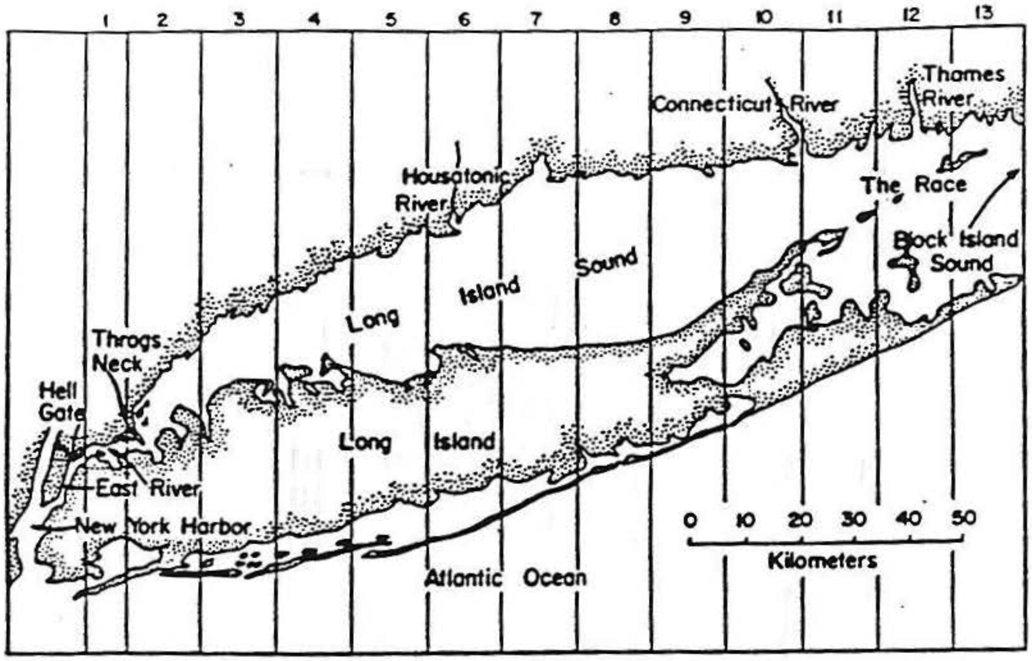


Fig. 2: Locator map of Long Island sound. The 13 sections represent zones which were modeled for nutrient transport and uptake (from Bowman, 1976d).

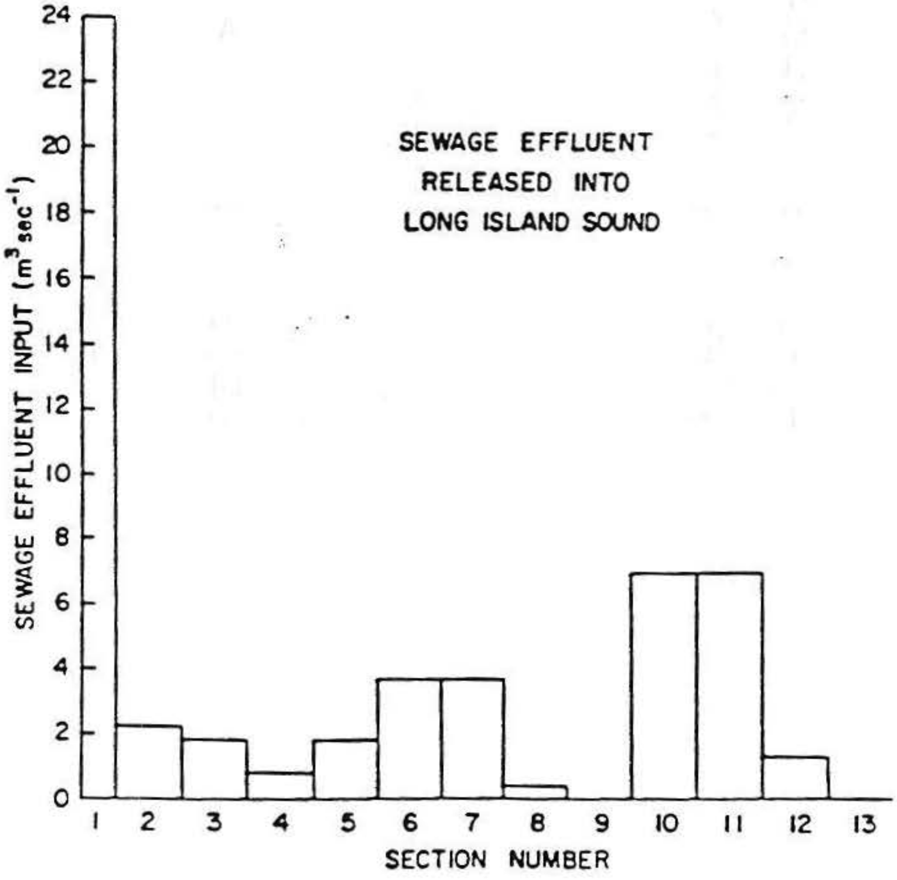


Fig. 3: Local distributions of sewage effluent released into the upper East river and Long Island Sound (from Bowman, 1976d).

Long Island Sound, representing the largest source of contamination to the western Sound, exceeding by an order of magnitude local releases around its perimeter Bowman, 1976a). However, since the population densities along both the north and south shores of the Sound increase exponentially towards New York City, local sources of contamination are locally significant.

Other contributing factors are:

i) tidal circulation in western Long Island Sound approximates a standing wave, where tidal *currents* become progressively weaker towards the confluence with the upper East River (although tidal *ranges* become progressively larger). Hence flushing by both dispersion and vertical mixing diminishes westward (Bowman, 1976b);

ii) the estuarine circulation in western Long Island Sound, driven by the input of fresher Hudson River water through the East River also diminishes westward, restricting the eastward export of surface waters to central Long Island Sound and the westward replacement of bottom water from central Long Island Sound (Wilson, 1976);

iii) the surface area of western Long Island Sound decreases westward, diminishing atmospheric exchange of dissolved oxygen (DO) with its surface waters;

iv) wind fetch over Long Island Sound decreases westward, due to the reduction in surface area, diminishing vertical mixing in the water column by wind waves;

v) high summer temperatures in western Long Island Sound and weak winds promote strong stratification and also diminish vertical exchange (Weyl, 1976);

vi) the freshwater runoff from the Hudson River is at a minimum in summer which also diminishes the estuarine circulation in western Long Island Sound and reduces the flushing of New York Harbor (Bowman, 1976c);

vii) the East River, meandering through the heart of the city and isolated from the ocean by narrow and poorly flushed waterways, has tides whose daily back and forth excursions are only 70% of its own length (Bowman, 1976b); correspondingly it is unable to flush itself of high concentrations of sewage. Dispersion is poor, releases are high, and contaminants, including inorganic nutrients, are at unacceptable levels (Bowman, 1977).

Calculations show that approximately 5% of the water in the East River originated from a sewer outfall (Bowman, 1976a; Weyl, 1976).

Thus the exponential westward increase in local nutrient loadings, the poor location of sewage treatment facilities (particularly in the East River), problems associated with combined sewers, and the poor flushing of the western Long Island Sound, East River, New York Harbor and Hudson River waterway complex, all contribute to an inability of the system to dissipate effluents and to a massive overloading of the natural ecosystem.

The combined effects of these influences are reflected in the high levels of inorganic micronutrients, eutrophication and summer hypoxia found in the western basin (Figs. 4 and 5; Bowman, 1977).

II. REGIONAL TIDAL CIRCULATION AND ASSOCIATED VERTICAL MIXING

New York Harbor has two major openings to the Atlantic Ocean where tidal currents are significant; the Verrazano Narrows and the East River. Tidal currents through these two navigable waterways are fundamentally different.

The tide in the Hudson River (including New York Harbor) is best described as a progressive wave, which propagates up to the Federal dam at Troy, NY. Maximum flood and ebb currents in the lower Hudson occur at high and low tide, respectively.

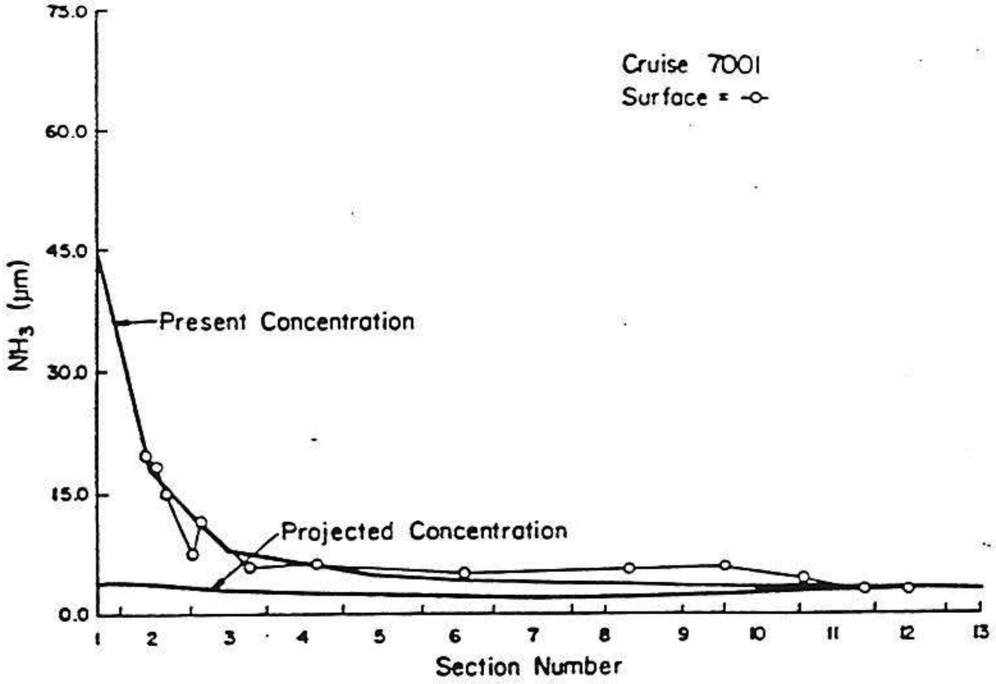


Fig. 4: Present and projected winter ammonia concentrations after lock emplacement (from Bowman, 1976d).

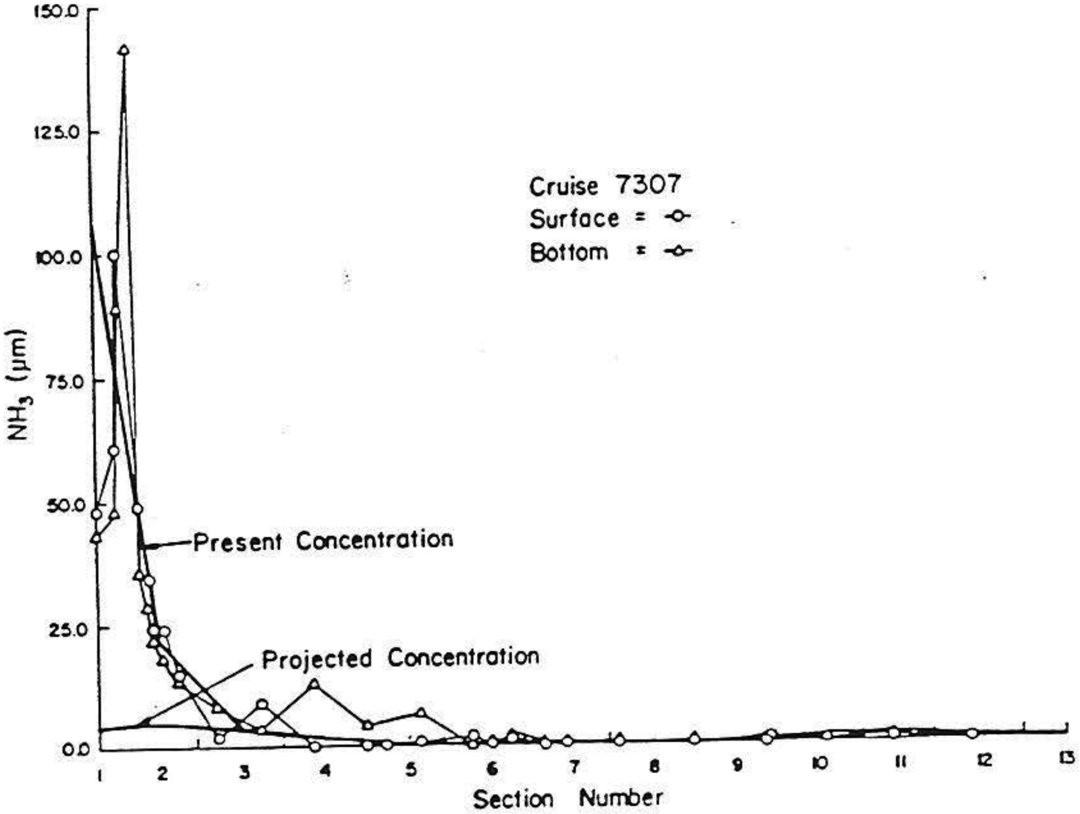


Fig. 5: Present and projected summer ammonia concentrations after lock emplacement (from Bowman, 1976d).

Because of its resonant length and constricted western end, the tide in Long Island Sound approximates a standing wave, where maximum flood and ebb currents occur at mid-tide, on the rising and by both dispersion and vertical mixing falling tide, respectively. The significance to this discussion is that a 3 hour time difference exists between the times of high tide at the two ends of the East River (Bowman, 1976b).

The East River (actually not a river at all, but more properly designated a tidal strait connecting New York Harbor to Long Island Sound) thus experiences large surface slopes along its length (hydraulic head) which drives strong tidal currents (6 to 7 knots near Hell Gate) back and forth twice a day.

III. FIXED STRUCTURES AND TIMED RELEASES OF SEWAGE TO ALLEVIATE HYPOXIA IN WESTERN LONG ISLAND SOUND

Vertical Stirring Poles

It has been suggested that a field of vertical poles with stirring fins attached, planted in western Long Island Sound might be effective in reducing summer stratification, hence reducing hypoxia. The idea is that turbulence created by strong tidal currents flowing past the poles would stir up the water column and lead to aeration of bottom waters.

To be effective, stirring poles would have to be spaced apart a distance considerably less than one tidal excursion. They would have to be erected in rows parallel to the axis of the Sound, oriented approximately northeast-southwest (the tidal excursion is that distance a particle of water moves back and forth each tidal cycle). This would mean an axial spacing of about 1 km, and a cross-channel row spacing of approximately 100 m.

This thicket of poles would need to extend from Throgs Neck Bridge eastward to about Oyster Bay. The generation of tidal turbulence by obstructions in the water column is proportional to the cube of the current velocity, which in western Long Island Sound peaks at about 40 cm s^{-1} (U.S. Department of Commerce, 1973). Unfortunately, this speed is insufficient to mix the water column in summer against buoyancy forces when the stratification is strongest (Bowman and Esaias, 1981, Bowman et al, 1981).

The hazards to safe navigation, and the extraordinary expense of maintaining *several thousand* lighted structures peppered all over western Long Island Sound, make this solution simply impracticable. By the same reasoning, mixing around bridge piers is a very localized phenomenon, and would make no measurable difference in alleviating the overall hypoxia problem in western Long Island Sound.

We can safely discard this option.

"Dutch Doors" across the East River

It has also been suggested that a barrier laid across the upper East River designed to block only the upper portion of the water column might catch and hold back more polluted surface waters from entering Long Island Sound. This might work in a highly stratified system, where a strong density contrast existed to separate surface and bottom waters, but it certainly would not be effective in the East River which is only marginally stratified. Also the turbulence generated by the barrier itself would stimulate further mixing of contaminated surface water into the lower layers as water plunged under the obstruction.

The structure would not be effective and make navigation impossible.

Timed Sewage Releases

Some benefit could be attained by restricting sewage releases in the East River to periods when the tidal currents were flowing towards New York Harbor. This pulsing of discharges would provide some relief to western Long Island Sound, but would hardly excite the citizens of New York City as they witnessed a doubling of the sewage loading to their Harbor.

The benefits to Long Island Sound would be tempered by background concentrations of sewage originating from outfalls around the Harbor (apart from the East River itself) continuing to diffuse through the River into the Sound by tidal dispersion.

It is an option worth investigating further, but the benefits are anticipated to be relatively minor for Long Island Sound and deleterious for New York Harbor.

IV. TIDAL LOCKS TO ELIMINATE HYPOXIA

The Tidal Locks concept is based around increasing tidal circulation and dispersion throughout the New York Harbor- Hudson River- Harlem River- East River- western Long Island Sound complex by rectifying the tidal currents of the East River into a one-way current, and using this new current to flush out the complex.

The East River, flowing through the heart of the city, is not really a river at all, but is more correctly described as a tidal strait. Tidal currents co-oscillate back and forth twice daily, with only a small net flow resulting. As far as dispersing effluents are concerned, these oscillations serve mainly to distribute the high levels of sewage waste locally released into the River in both directions; into western Long Island Sound on flooding tide, and into New York Harbor on ebbing tide. Thus present tidal motions and poor flushing are ineffective in dispersing contaminants out to sea which of course was the desired result of those who constructed the treatment plants in the first place.

The East River would become much more effective in dispersing high concentrations of sewage effluents and associated nutrients out to sea if the present tidal co-oscillations could be harnessed, and modified into a one way current, more like a real river, and used to flush clean the western Sound and New York Harbor *both at the same time.*

This would be accomplished by building a system of ship locks and tidal gates across the upper River near the location of the Bronx-Whitestone Bridge (Fig.1). The locks and gates would be opened and closed in synchronism with the semi-diurnal tidal currents, so as to convert the present back and forth tidal currents into a pulsing uni-directional current (Fig. 6). East River currents would flow to the Harbor for approximately six lunar hours (6 hr 12 min) and then be zero for the next six lunar hours.

Thus twice each day a large volume of Sound water (100 million m^3;) would displace approximately 30% of the water in the New York Harbor. For comparison, the mean fresh water discharge of the Hudson River displaces only 7%, and the tidal prism 20% of the volume of the Upper Bay (Bowman, 1976d).

A cartoon of ships navigating the locks is shown in Fig. 7. A side view of water levels in the East River (Fig. 8) shows both present and future tide levels and currents during ebb and flood phases of the tidal cycle. During ebb tide (i.e., westward flow), the gates would be fully open allowing an unhindered flow of Long Island Sound water into New York Harbor. Ships would pass freely.

Six hours later the gates would be closed at slack water, completely blocking any return of New York Harbor water back into the Sound. Ships would negotiate the locks.

This new current would draw clean central Long Island Sound water through the western Sound, into New York Harbor and out to sea through the Verrazano Narrows.

Ship locks are commonly used to facilitate safe navigation through difficult waterways that possess exceptionally large tidal ranges (e.g., the ports of Southhampton and Plymouth, England, Amsterdam and Rotterdam in The Netherlands), impassable steep rivers, gorges, canyons and waterfalls (e.g., the Sault Sainte

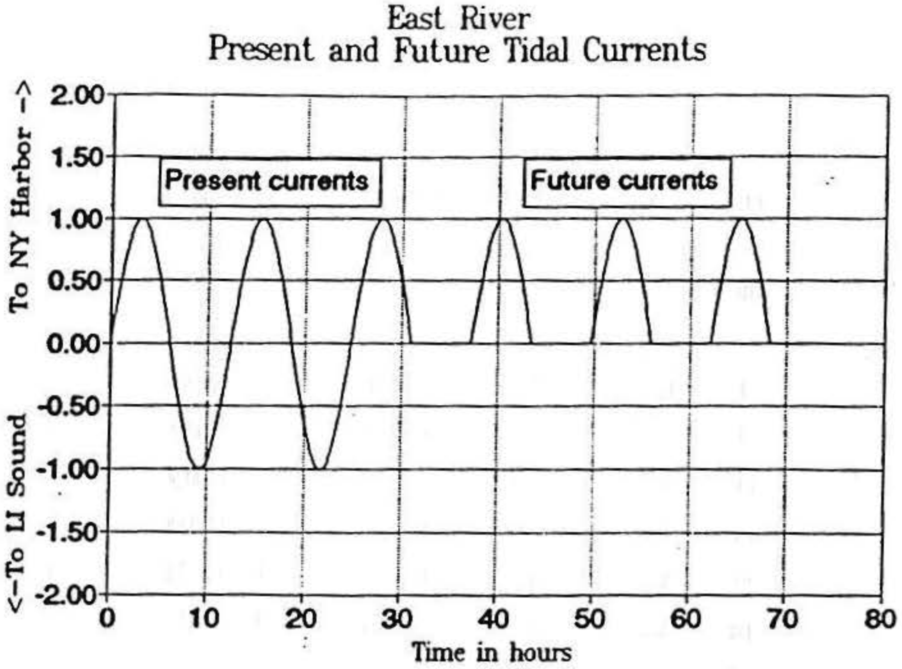


Fig. 6: Schematic of rectification of East River tidal currents. The left side of the diagram represents present conditions, and the right side conditions after locks are in operation.

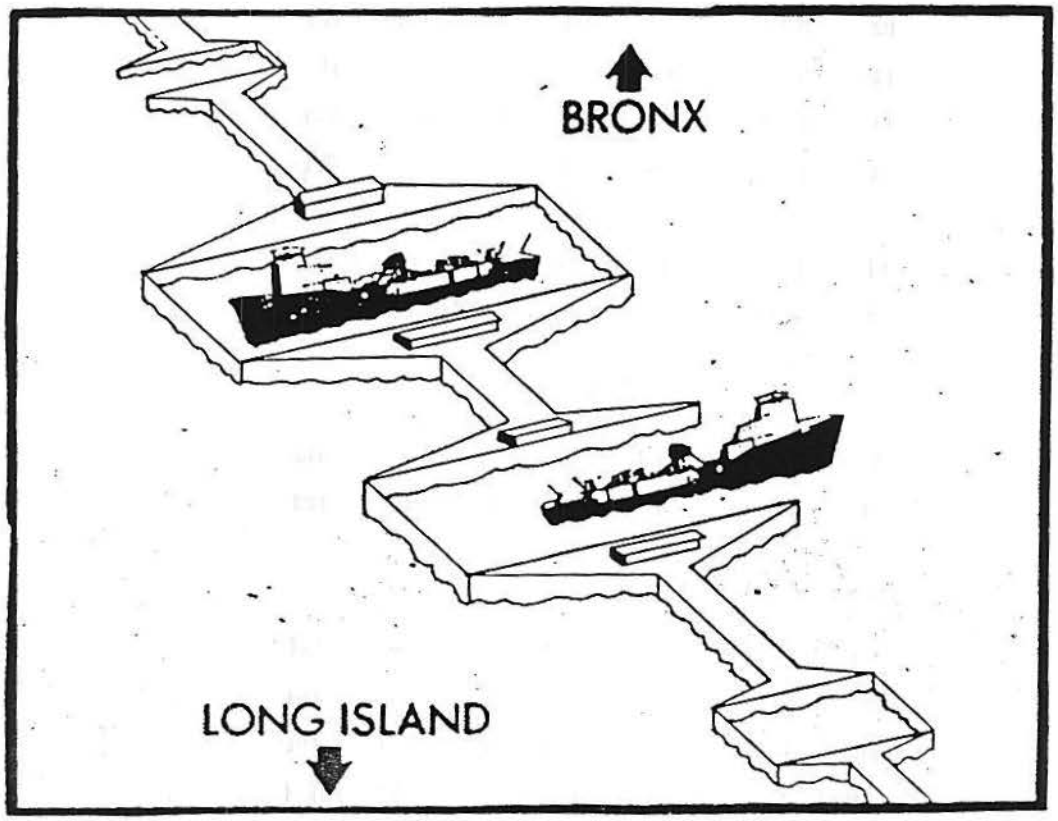


Fig. 7: Sketch of ships negotiating East River locks (from Newsday, 2 December 1975).

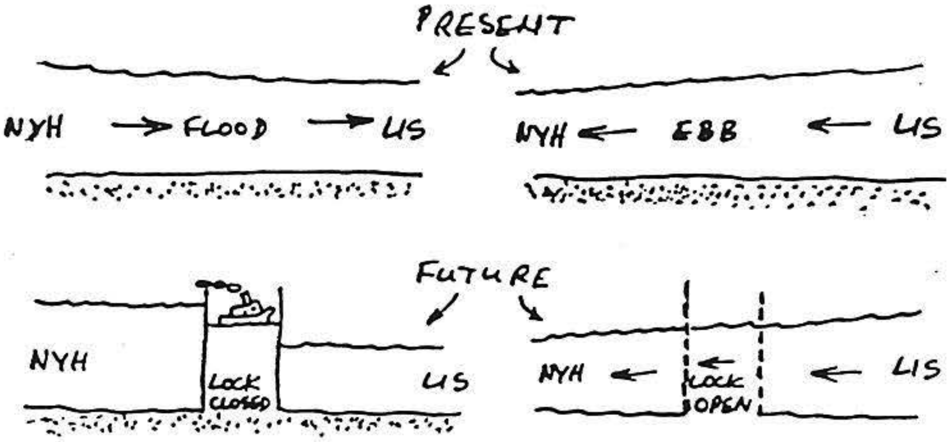


Fig. 8: Side view of tidal elevations for flood and ebb tides in the East river before and after lock construction.

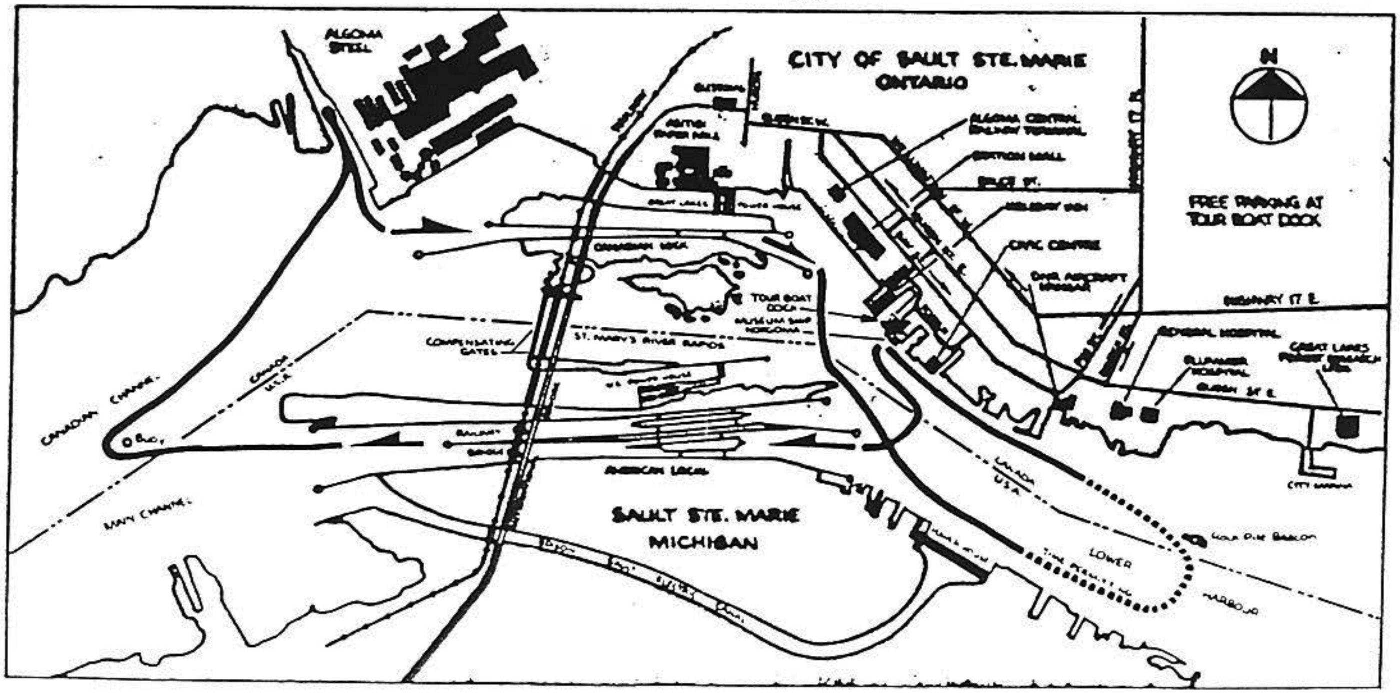


Fig. 9: Map of th

Marie locks between Lakes Superior and Huron; Fig. 9), and connected ocean basins with differing sea levels (e.g., the Panama Canal).

Our purpose in recommending locks across the East River is not so much to enable safer navigation (although this would be a useful side effect), but rather to:

i) *block all effluents* released into the East River and New York Harbor from entering western Long Island Sound (which is by far the Sound's largest source (Bowman, 1976a);

ii) *continuously replace all the otherwise eutrophic waters of western Long Island Sound* with central and eastern Long Island Sound water (total replacement of the waters of western Long Island Sound would take about one month);

iii) *flush out the East and Harlem Rivers* with their high ambient levels of pollution twice a day with central and eastern Long Island Sound water;

iv) *daily replace 30% of the total volume of water in New York Harbor* with central and eastern Long Island Sound water.

Tidal locks would effectively double the flushing rate of New York Harbor. Nutrient concentrations in New York Harbor would immediately drop by 50% (Bowman, 1976d).

Even though at first sight it might seem that the increased sewage loading (that amount currently leaking into western Long Island Sound from the East River,) would make matters worse in New York Harbor, it turns out that the increased flushing of the harbor more than compensates and quickly dilutes any increase in loading.

It is interesting from a historical point of view to diverge for a moment and comment briefly on the history of the Shinnecock Canal located at Hampton Bays on the south fork of eastern Long Island. As early as 1652 the history of Southhampton records attempts of local authorities to release landlocked waters in Shinnecock Bay, and even earlier attempts by the local Indians to open and maintain a channel between Peconic and Shinnecock Bays (State of New York, 1924).

A half mile canal was completed in 1893 (Fig. 10). The canal was fitted with tidal gates designed to allow clean Peconic Bay water to flow into polluted Shinnecock Bay (but to prohibit the return flow) in order to improve the shellfish harvest in Shinnecock and Moriches Bay. Apparently the results were pleasing "..a most gratifying effect on the oyster growth in Shinnecock Bay, and that whereas three years before there had not been probably a single barrel of these shellfish in the bay, in the previous year 25,000 bushels of seed oysters had been taken out, besides thousands of barrels of mature oysters of the finest flavor, valued at $100,000" (State of New York, 1924).

The tidal gates were constructed near the swing bridge; passage by boats was restricted to a short period around slack water.

In 1919, the State of New York appropriated $35,000 for the construction of a lock to augment the tidal gates, to allow safe passage of boats at any stage of the tide. New locks were placed into operation in 1968 and continue in operation to this day (Fig. 11).

V: EXPECTED IMPROVEMENTS IN WATER QUALITY

The predicted improvements in water quality in Long Island Sound and New York Harbor after emplacement of East River tidal locks were obtained by evaluating the drop in concentrations of dissolved inorganic nutrients (NH3, N02, N03), using vertically integrated mass balance models (Bowman, 1976d). Nutrients are relatively easy to measure experimentally, and have direct influences on the eutrophication and biochemical oxygen demand of receiving waters.

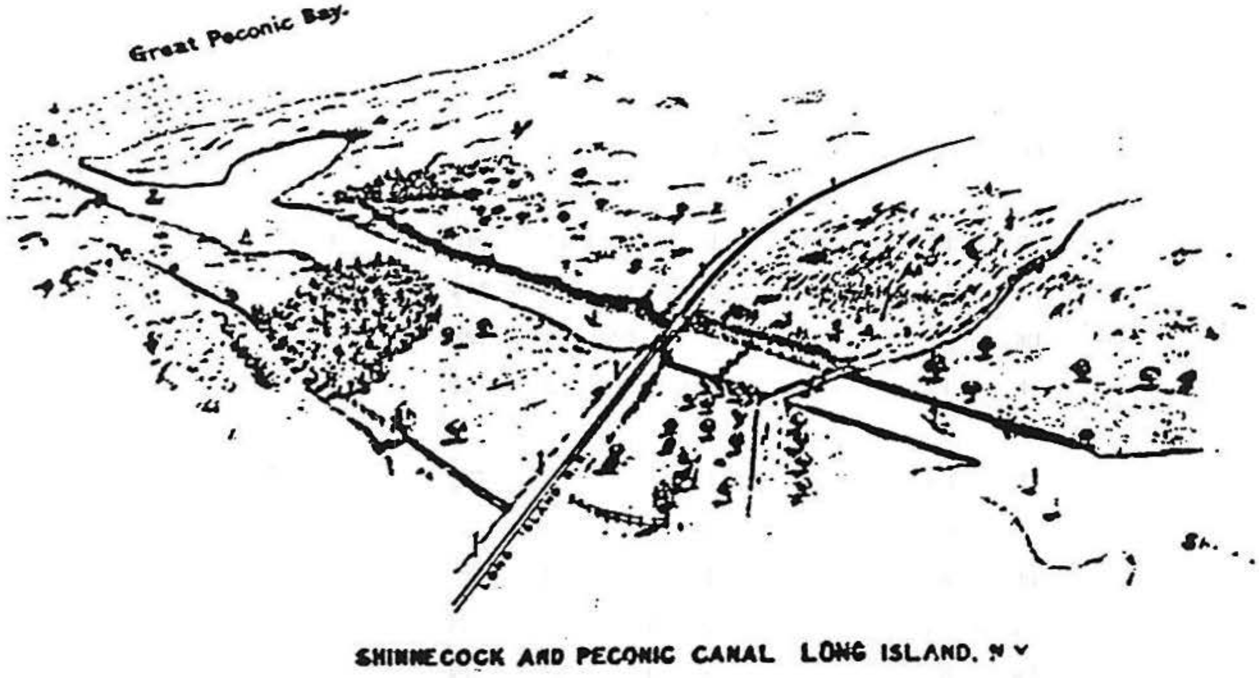


Fig. 10: Sketch of the early Shinnecock Canal (from State of New York. 1924).

Fig. 11: Photograph of the present Shinnecock Canal locks.

Present nutrient concentrations in western Long Island Sound and New York Harbor reflect the combined effects of natural processes such as primary production, respiration and regeneration, modified by anthropogenic inputs from sewage, agriculture, and aerosols (Bowman, 1977). Predicted future concentrations represent the solutions to equations that describe the effects of the modified circulation and dispersion on these existing inputs, both for winter and for summer conditions.

The models were constructed around coupled vertically-integrated steady-state, tidal dispersion and advection, water, salt, and nutrient balance equations for New York Harbor and each of 13 representative regions of the Sound stretching from Throgs Neck Bridge to the Race (Fig. 2).

Present and projected ammonia concentrations in the upper East River and Long Island Sound are shown in Figs. 4 and 5. The open circles represent measurements gathered along the axis of the Sound on MSRC sampling cruises in winter and summer. The upper solid line are the model's simulations of present ammonia concentrations, and the lower lines are the model's predictions of concentrations after emplacement of the locks.

The expected reductions in ammonia concentrations are large for western Long Island Sound. Concentrations at Throgs Neck are predicted to drop from typical present values of ~45 uM (winter) and ~100 uM (summer) down to ~ 3 uM (*improvements of 93% and 97%, respectively*). Elsewhere concentrations remain low and almost uniform along the length of the Sound, with only slight increases at both ends, reflecting the effects of local sewage inputs from western Long Island, and in eastern Long Island Sound from sources in the Connecticut River basin.

The expected drop in the concentration of other nitrogeneous nutrients (N02, N03) are equally impressive; e.g., nutrient levels would drop 94% to 97% in the western Sound.

As mentioned above, the expected reduction in nutrient concentrations in New

York Harbor, although not as great as those in western Long Island Sound, is still significant. A 50% reduction from present averaged levels is predicted, *without any other changes made to the loading from all sources around the Harbor, including from New Jersey.*

Calculations have yet to be made on the expected improvement of bottom DO levels in western Long Island Sound after lock emplacement, but they can be expected to improve to values typical of central Long Island Sound in summer (>3 ppm).

In summary, inorganic nutrient concentrations will drop 93% to 97% in the western Sound and 50% in New York Harbor, one month after lock operations commence.

VI. ENGINEERING AND CONSTRUCTION ASPECTS

A detailed discussion of the engineering design of tidal locks is beyond the scope of this paper. A few factors are worth pointing out, however. The site of a dam would need to be in the upper East River, preferably east of the four large sewage treatment plants, certainly east of Hell Gate where strong tidal currents would make navigation on ebb tide through an open lock hazardous. The preferred location would lie between Throgs Neck and Bronx-Whitestone Bridges.

The width of the East River is 900 m near the Bronx-Whitestone Bridge (Fig. 1), with an average depth 7 m below mean low water (Jay and Bowman, 1975). The maximum hydraulic head across the River is 1.5 m (5 feet; Jay and Bowman, 1975). This is the the maximum height difference that would exist across the locks, relatively modest compared to many locks (e.g., 21 feet for the Soo Locks). Tidal currents in the shipping channel in this location peak at ~ 1.6 knots (80 cm s^{-1}; U.S. Department of Commerce, 1956), which is an acceptable speed for safe transit through an open lock. There would be no currents near the locks when closed, so navigation would be straightforward.

Four locks would probably be needed. Two large locks 200 m x 30 m near the center of the channel would handle major shipping in two directions, and two smaller locks 25 m x 8 m near the banks would take lighter commercial and recreational traffic (Fig. 5). Transit through the locks would take approximately 20–30 minutes. Several ships could traverse each lock at the same time, depending on their size.

The gates would be designed to provide minimal resistance to flow when open. The use of self opening and closing louvers across those sections of the dam not served by locks would serve this purpose.

Each major locking operation would release about 12,500 m^3 of East River water into the Sound, equivalent to the flow over a 5 seconds period. The leakage of contaminated water is entirely negligible.

Unconsolidated and semi-consolidated bottom sediments in western Long Island Sound of Pleistocene and Cretaceous age rest on a Precambrian and Paleozoic crystalline bedrock surface that slopes to the southeast (Grim et al, 1970); these should provide no major engineering obstacle to the construction of locks in the area. Lock construction methods are well established, with engineering expertise readily available in the USA, Canada, Great Britain and Continental Europe.

A detailed analysis of the engineering design and costs are beyond the scope of this paper. A rough estimate gives construction costs close to $1 billion. This still compares favorably with funds expended over the last decade on upgrading and new construction of New York City sewage treatment plants (over $5 billion).

VII: OPERATIONAL ASPECTS

Navigation through the Locks

As mentioned above, ships would be free to pass unhindered through open locks

50% of the time (when water was flowing out of the Sound). During the other 50% of the tidal cycle, ships would navigate through the closed locks (in either direction). According to P. Jones (pers. comm.), a Great Lakes navigator with experience taking large ore freighters (greater than 200 m (600 ft) in length) through St Lawrence Seaway locks, most of the transit time is spent creeping the ship into the locks (up to one hour), and steaming out the other side. It takes only about 10 more minutes to fill or empty a typical lock with a rise or fall of 8 m (25 ft).

East River vessels are restricted in size by the Hell Gate narrows, and are obviously much more maneuverable than Great Lakes freighters. Fundamentally lock navigation is a very safe and straightforward operation.

If a ship wishes to travel downstream, the upper gate is opened, the ship noses into the lock, the gate is closed, and the water slowly released from the interior of the lock through discharge ports into the downstream side of the river. When the water level inside the lock equals that on the down-side, the lower gates are opened and the vessel emerges under its own steam.

When a ship wishing to travel upstream, it enters through the open lower gate, the gate is closed and the lock filled with water from the upstream side of the river. When the levels equalize to the upper level, the upper gate is opened and the ship emerges.

No pumping of water is required; the whole operation functions solely by gravity. The only power requirement is to operate the hydraulic gates. Water pressure jams the gates closed, and it is impossible to open them unless the levels are equalized.

Operation and Maintenance Considerations

The only machinery on the locks would be the moving gates and the control valves for filling and emptying. Winches would also be required for maneuvering

and securing ships within the locks. Automatic hinged louvers across the balance of the channel might pose more of a maintenance problem, since they could be prone to jamming through corrosion or collision with large pieces of floating debris. Catchment screens could be placed both sides of the louvers to minimize interference.

Operational manpower requirements would be two lock masters to control ship movements and operate the gates, plus several personnel to secure the ships. The locks could be made self financing through imposition of a toll.

XIII: SIDE EFFECTS

Potential Navigation delays and/or congestion

The East River, the second entrance to the Port of New York, has always been a highly congested and dangerous shipping route (Rattray, 1973). A survey conducted by the U.S. Coast Guard (1972) showed some 1,065 vessels plying the East River's Hell Gate channel during one 69 hour period that January, equivalent to one vessel passing every four minutes. Another Coast Guard survey during one week in the summer of 1974 measured an average of eight vessels per hour passing the Hell Gate region (Sutherland, 1975).

Long Island Sound ports handled 20 million tons of cargo in 1964, largely consisting of shallow draft barges (US Army Corps of Engineers, 1965) and has increased slightly since then (much of this traffic did not pass through the East River, however). This figure should be compared to 14 million tone handled annually by the Port of Amsterdam, a port entirely isolated by locks from the sea.

During the fiscal years 1969-1972, 46 collisions, rammings and groundings involving 80 vessels occurred. Fifteen of the 46 incidents were considered to have been preventable by some form of shore-based vessel traffic management or assistance (Hickey, 1975). The construction of ship locks across the East River would necessitate new traffic management policies. Traffic congestion is now such that these are necessary anyway.

The river would become safer for navigation, both from improved traffic control, and from reduced navigation hazards at Hell Gate (where currents peak at 7 knots) since 50% of the time currents would be almost zero.

Effects on Tides and Currents in the Region

Obviously there would be significant modifications to tidal currents throughout the greater metropolitan region. Tides in Long Island Sound would vary little, since as mentioned above, the flow through the East River is only 2% of the Sound's primary tidal exchange with the Atlantic Ocean through the Race.

New York Harbor tidal *ranges* would not be expected to change more than a few centimeters from present levels. A readjustment of tidal *currents* would occur, such that flooding tide waters in New York Harbor would continue up the Hudson River, rather than splitting into the lower East River as presently occurs (Fig. 12). Maximum flood tidal currents would be weaker than at present, since a relatively small amount of water would flow up the East River, sufficient only to raise the water to high tide levels, since the locks would be shut.

On ebbing tide, East River currents would add to Hudson River currents to give ebb currents through the Verrazano Narrows similar to what they are at present. A detailed description of tidal current alterations could be readily obtained with the MSRC numerical tidal model (e.g., Bowman et al, 1980).

Tidal currents would change but tidal ranges would not. No rise in sea level would result.

Increased Salinity in Long Island Sound and New York Harbor

The slow westward movement of new Atlantic Ocean water through Long Island Sound induced by the tidal gates in the East River would increase the salinity of

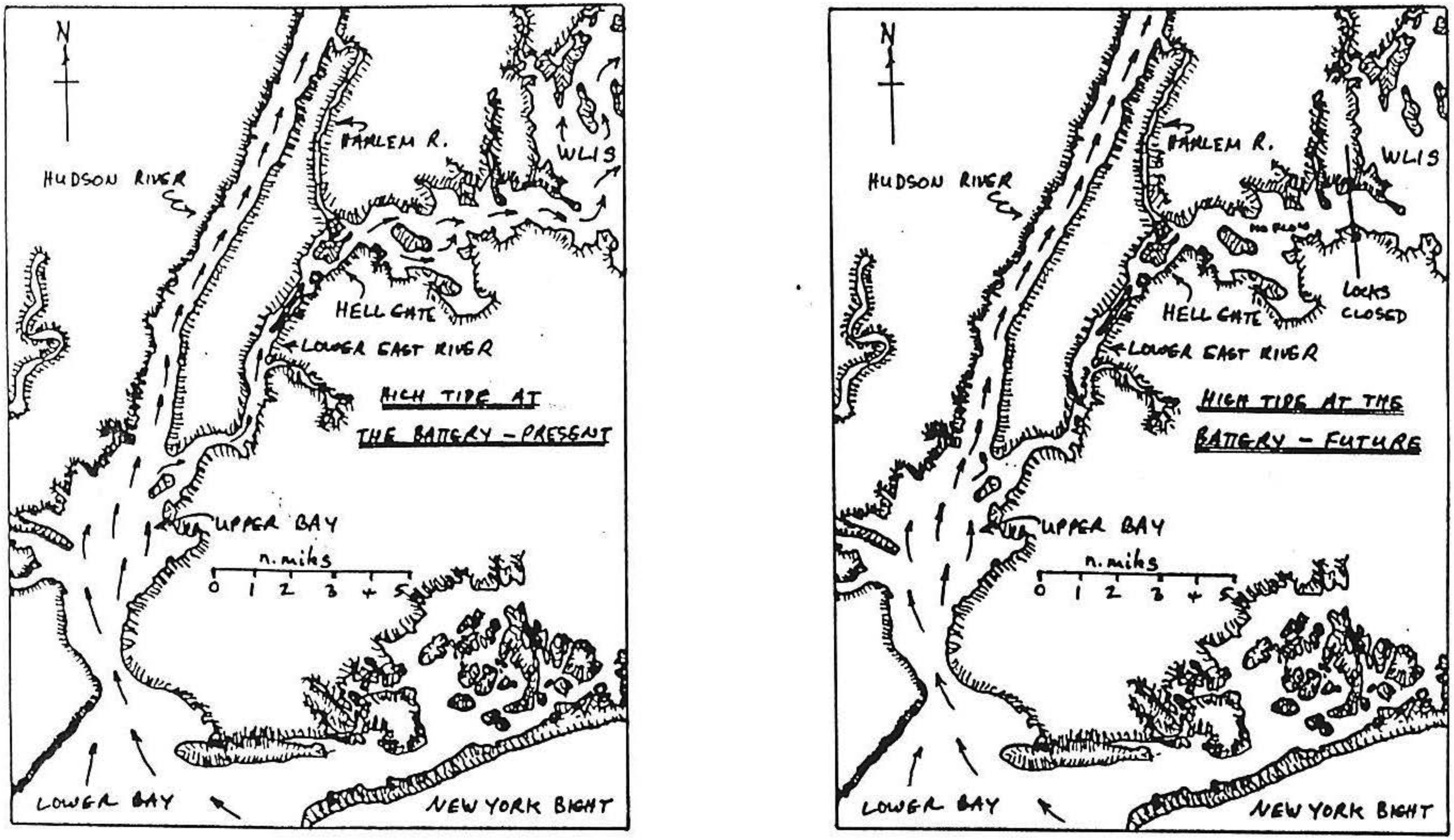


Fig. 12: Sketches showing expected changes in the tidal circulation in New York Harbor after locks are put into action.

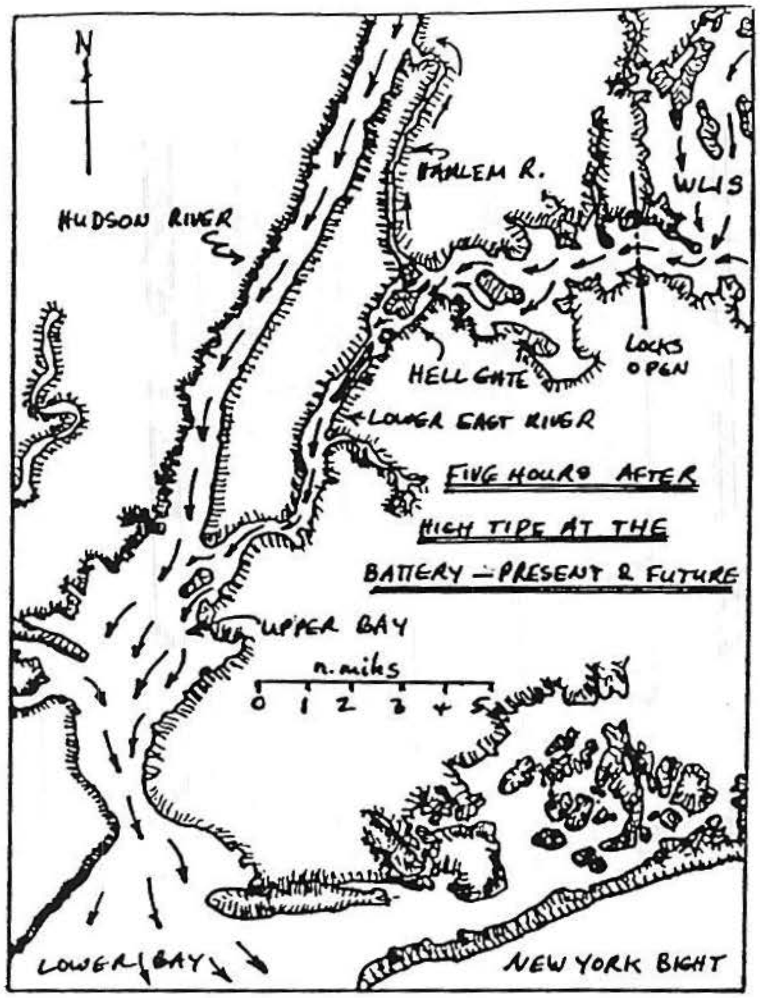


Fig. 12 (cont'd): Tidal circuation 5 hours after high tide at The Battery, present and future (adapted from U.S. Dept of Commerce, 1956).

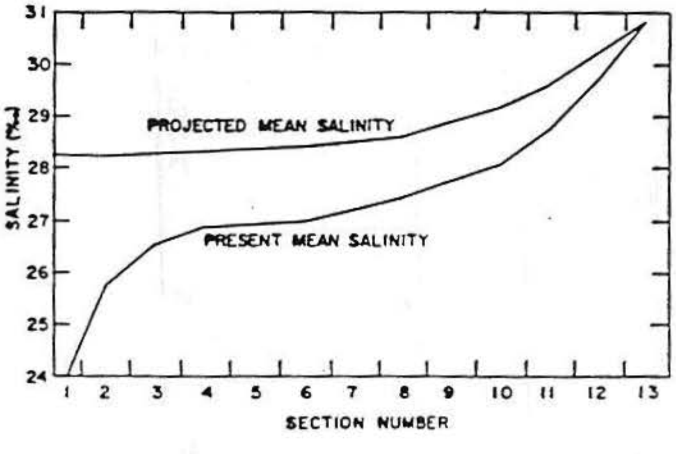


Fig. 13: Predicted increase in Long Island salinity after installation of tidal locks.

the Sound by a small amount. In addition, the elimination of water of Hudson River origin presently entering the western Sound would contribute to this rise in salinity.

This increase in Sound salinity was estimated by Bowman (1976d) to be 4.5 °/₀₀ immediately east of the locks, less than 2 °/₀₀ over most of the Sound, and reducing to zero near the Race (Fig. 13).

Long Island Sound is a partially mixed estuary (Wilson, 1976). Such estuaries support a characteristic two layered non-tidal circulation with a surface outflow, and a compensating return flow at depth. This circulation is driven by upstream fresh water sources. Tidal locks would effectively shut off the input of fresher water originating in the Hudson River, and hence would reduce or eliminate the estuarine circulation in the western Sound. Conditions in the western basin would approximate those of a coastal embayment with a reduced horizontal density gradient in the central and eastern regions maintained principally by the outflows of the Housatonic and Connecticut Rivers.

Models need to be run to ascertain the effect on dissolved oxygen (DO) levels from reducing the estuarine circulation, but the effect is likely to be beneficial, since the salinity stratification will be reduced. Predation of oysters by oyster drill worms would be reduced, as would other salinity sensitive marine borers which attack wooden pilings.

Increases in salinity would vary between zero and 4.5 o/oo.

Increased Sewage Loadings to the Bight

It might be argued that diverting East River effluents out of the Sound and into the Harbor, and subsequentially to the Bight Apex would only increase loadings to those areas. While it is true that the total volume of sewage effluent would *increase*, the concentrations would *decrease*, because of the dilution by

Sound water. The two effects compete with each other; increased loadings on one hand, dilution on the other. ***Fortunately, dilution wins*** . All communities should benefit from cleaner water, including those on the New Jersey shoreline and along the Atlantic coast.

Contaminant concentrations would decrease in the New York Bight Apex and the New Jersey shoreline.

IX: OTHER LOCK/BARRIER SYSTEMS WE CAN LEARN FROM

As mentioned above, Shinnecock Canal locks have been safely operated for over 70 years.

It is interesting to note the existence of two other major engineering projects already built or under construction for flood control around large cities. Floodgates have been constructed across the Thames River in England at a cost of $500 million to block storm surges from inundating the City of London. The gates normally lie flat on the river bed, but are raised mechanically to block abnormally high tides.

Several famous Venetian monuments are threatened by the long term rise in sea level and by storm surges originating in the Adriatic Sea. Hollow water filled caissons lie on the floor of the channels linking the Venetian lagoon with the sea. Air is pumped in during storm weather, making the caissons buoyant and causing their tops to swing upwards, closing off the lagoon. Construction costs were $1.5 billion.

X: WHAT FURTHER SCIENTIFIC RESEARCH IS NEEDED?

The predictions and recommendations made in this paper are based on scientifically sound but relatively unsophisticated models and calculations. A major scientific study needs to be developed to investigate all aspects of the proposal using modern analytical and modeling tools. A list of topics would include investigations of:

i) modifications to tidal heights and circulation patterns in western Long Island Sound, the East river, New York Harbor and the Hudson River;
ii) changes in estuarine circulation and vertical mixing in western Long Island Sound, the East river, New York Harbor and the Hudson River;

iii) alterations in temperature, salinity and stratification patterns in western Long Island Sound, the East River, New York Harbor and the Hudson River;

iv) changes in nutrient concentrations, primary and secondary production, and DO levels in western Long Island Sound, the East River, New York Harbor and the Hudson River;

v) environmental implications for the New York Bight Apex and the New Jersey shoreline;

vi) ecological studies of potential alterations in flora, fauna, and fish migration patterns in western Long Island Sound and the Hudson River;

vii) calculations on the expected drop in coliform bacteria concentrations from the reduced sewage concentrations, including an estimate of how many presently closed Sound shellfishing beds might be reopened.

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Use of Constructed Wetland Technology for Treatment of Stormwaters and Wastewater Effluent: Summary of Considerations and Potential Applications to Alleviate Seasonal Hypoxia in Western Long Island Sound

by

Jennie C. Myers

USE OF CONSTRUCTED WETLAND TECHNOLOGY FOR TREATMENT OF STORMWATER AND WASTEWATER EFFLUENT:

SUMMARY OF CONSIDERATIONS AND POTENTIAL APPLICATION TO ALLEVIATE SEASONAL HYPOXIA IN WESTERN LONG ISLAND SOUND

A White Paper
Presented to the U.S. Environmental Protection Agency
Region I
Boston, MA

by

Jennie C. Myers,
Cambridge, MA

November 20, 1991

I WETLANDS AND WATER QUALITY

Introducton and Background

The use of created wetlands as a low-cost method for final wastewater renovation and for treatment of polluted stormwater runoff has received considerable attention in recent years. In the U.S., approximaty 150 communities currently employ, or are planning to use, constructed wetlands as a component of their wastewater treatment strategy (Reed, in Small Flows Clearinghouse, 1990). A large body of literature has developed on the design, use, and performance of these systems.

Although applications to stormwater management have been less widespread, a number of reviews have been prepared describing the performance and treatment efficiencies of a range of systems put in place to meet emerging regulatory standards (e.g. Stockdale, 1986; RIDEM, 1989; State of Maryland, 1987; Livingston, 1989). Other reviews have considered the use of natural wetlands for treatment of stormwater and wastewater (e.g. Newton, 1989; Chan, et al., 1989) or have focused on cost-effectiveness of stormwater treatment technologies generally.

In both applications, development and use of systems has preceded the ability to clearly evaluate many basic aspects of system function, or to accurately predict key performance factors, incuding treatment efficiency. Uncertainty is due to several factors: the young state of the art of applicable areas of wetland science, the tremendously varied characteristics of systems in place and the circumstances in which they operate, a lack of long-term monitoring data, and a lack of consensus regarding interpretation of data and its application to diverse needs.

Nevertheless, there is sufficient agreement as to the potential benefits offered by existing natural wetlands and by created wetland systems in water quality enhancement to suggest further investigation of created wetland technology for application to control of hypoxia in Western Long Island Sound. Although it was prepared on an extremely compressed schedule, this paper will attempt to shed light on some basic questions concerning potential application of created wetlands technology to Long Island Sound, as they relate to reduction of nitrogen loads from urban stormwater runoff and wastewater only. (Numerous other issues are important in a feasibility evaluation but are beyond the scope of this effort.)

Questions to be addressed include:

1) In general, what is the "state of the art" of each technology?
2) Do reported removal efficiencies indicate that use of these technologies could make a significant difference in management of seasonal hypoxia in the western Sound?
3) What general land area requirements would be involved for use of the technologies?
4) Are created wetlands a permanent sink for nitrogen?
5) What treatment contributions may be offered by existing natural wetlands?

Summary of Treatment Processes

Urban stormwater is highly polluted. Sediment, phosphorus, nitrogen, septic effluent, organic compounds, refractory organics (pesticides and industrial chemicals), heavy metals, pathogens, petroleum hydrocarbons, and deicing chemicals have all been found in urban runoff in concentrations detrimental to receiving waters. Stormwater concentrations of suspended sediments, heavy metals, and BOD are equivalent to, or greater than, those found in secondarily treated wastewater (Silverman, 1983, in Newton, 1989) while oil and grease and organic chemical concentrations in stormwater depend upon land use patterns in the contributing drainage area (Stockdale, 1986).

Secondarily-treated wastewater has a higher organic content than stormwater; finer, less mineral particulates; and a lower nutrient content (Stockdale, 1986). Nevertheless many researchers have concluded that removal mechanisms in wetlands are quite similar between the two pollution sources, and that evidence regarding contaminant removal efficiencies in free-surface wastewater treatment wetlands may be applied to the evaluation of potential stormwater treatment efficiency.

Nutrient removal processes in wetlands involve physical, chemical, and biological action. In all of these processes, hydrologic variables are critical, and are a controlling factor in evaluating the feasibility of various treatment alternatives. Particularly for nitrogen, conditions appear to promote cycling and removal, in that the aerated water column and aerobic upper sediment layer foster nitrification, while reducing sediment conditions and the availability of the aerobic-anaerobic interface layer within the sediment promote simultaneous ammonification and denitrification (Chan, 1982, Patrick and Reddy, 1976).

Chemical adsorbtion of nutrients in stormwater and wastewater onto the surfaces of suspended particulates, sediments, vegetation, and organic matter has been shown to be a primary mechanism for removal of dissolved nutrients, particularly phosphorus, and for metals (Boto and Patrick, 1979). Adsorption processes are enhanced by increasing the contact of stormwater or wastewater with the substrate soils and organic matter. This is accomplished by providing long residence times for influent, shallow water depths, and even distribution of flow (Livingston, 1988).

Filtration processes occur as vegetation, sediments, and wetland biota remove particles from the water column. Brown (1985) related increased vegetation density to decreased flow velocity and enhanced settling of suspended materials. Sheet flow and reduced velocities promote filtration, as do system designs that provide for infiltration through a soil substrate or medium.

Sedimentation is extremely important in removal of particulate pollutants, including particulate nitrogen, phosphorus, oils and hydrocarbons, metals, and suspended solids. Sedimentation rates are closely related to system hydrology, flow velocity and path, and the magnitude of inflow (storm size). Again, slow sheet flow enhances sedimentation.

Biochemical processing is fundamental to nutrient assimilation in wetlands. Vegetated wetlands offer strong potential for biological uptake and a near ideal climate for microbial activity. In addition, plant productivity and nutrient uptake are high, as are decomposition rates. Sediment substrates offer large surface areas for biochemical activity and adsorption, and sediment oxygen content is frequently low. All of these processes are important in efficient nutrient processing and pollutant removal.

Microbes transfor ammonia to nitrate through nitrification, and from nitrate to nitrogen gas through denitrification. Although microbial activity can be considered ubiquitous in wetland environments, important rates of microbial activity depend upon numerous soil conditions and factors, including pH, organic content, oxgen content, temperature, and aeration regime (Groffman, et al., 1990). The loss of nitrogen to the atmosphere constitutes a true "sink" from the standpoint of water quality enhancement, and does not diminish over time. The rate of nitrogen loss to the atmosphere, however, may be affected by temperature, N concentration, oxygen concentration, presence of toxics, and other factors that may be influenced by wetland design (Knight, R.L, 1990).

Wetland vegetation, in particular, mediates nutrient interaction with sediment and litter layers, water, and air. Plant leaves, stems and roots take up dissolved forms of nitrogen, portions of which are formed into tissue or used to fuel plant processes. N forms are subsequently translocated to other plant parts, returned to the litter layer during senescence, stored over winter in the roots, denitrified in the sediment, potentially buried in sediment, or re-released into the water column.

Nitrogen Assimilation Processes in Wetlands

It is generally agreed that nutrient assimilation processes vary considerably among wetland types, among components of specific wetland assemblages, and from season to season, complicating estimates of the role of wetlands in nutrient and contaminant removal.

As of 1986, based on a review of data from ten northeastern marshes and bogs, Nixon and Lee concluded that it was not possible to arrive at a convincing assessment of the overall impact of the study wetlands on the water quality moving through them. The authors suggested that most wetlands appeared to input dissolved oxidized forms of oxygen and to export reduced nitrogen as ammonia and particulate organic matter. However the authors noted variations and exceptions to that trend, which have been further developed in more recent work.

Several investigatiors have found that nutrients are sequestered in wetlands during periods of the year when receiving waters are vulnerable to eutrophication. For example, based on controlled studies of the Delaware tidal freshwater marshes, Simpson (1983) concluded that despite their eutrophic state, the wetlands served to retain nutrients and heavy metals during the summer and fall in a manner which "clearly benefited the Delaware estuary by reducing nutrient availability precisely when the estuary is most stressed."

A great deal of research effort has been devoted to understanding the complex cycles within which nitrogen is transformed, stored, and released from wetland sediments and water environments. The four nitrogen species generally present in aquatic systems include organic nitrogen, ammonia nitrogen, nitrite nitrogen and nitrate nitrogen. Contributions of the different forms are difficult to quantify, and are dependent upon geologic and hydrologic circumstances and manmade features. Groundwater contributions may be significant. Surface runoff inputs may be extremely variable, and are a function of watershed size and land use practice. Nitrogen fixation within wetlands (a biochemical process in which plants produce usable N species) may be significant in certain areas, and is not confined to nitrogen limited environments (Keeney, 1973, in Lowry, 1979). Fixation rates, though, are affected by numerous factors. Valiela, et al. (1976) found nitrogen fixation to be reduced in salt marshes receiving ammonia inputs.

Nitrogen transformations within wetlands are extremely complex. Concentrations of the various forms may shift significantly, depending upon concentration inputs and rates of immobilization, ammonification, nitrification, denitrification, vegetative upate and release, and wetland hydrology. Numerous factors, such as bacterial action, substrate characteristics, pH, BOD, DO, and temperature affect each of these processes (Lowry, 1979).

Considerable scientific uncertainty surrounds several N cycling issues in natural wetlands which are important in approaching these questions (for both technology applications), to the extent that predicted performance in created wetlands is inferred from nutrient cycling evidence from natural freshwater wetlands. These issues, as articulated by Bowden (1987), Jordan (1991), Nixon and Lee (1986) and others will be summarized briefly.

a) Realistic estimates of nitrification and denitrification rates in freshwater wetlands are extremely scarce. Since a majority of estimates of denitrification rates in natural wetlands are based on experimental derivation of "potential," many estimates of the role of denitrification reported in the literature may have been overstated by as much as 40 to 1000 times (Tiedja, et al., 1982, Jordan,1991, in press).

b) Uncertainties regarding belowground production rates in freshwater make it difficult to project sediment N turnover.

c) Although dry deposition of N may have substantial importance in the N budgets of wetlands, especially close to urban centers, magnitudes of dry deposition are poorly understood. (It is estimated that 8% of the nitrogen load to Long Island Sound is due to direct atmospheric deposition on its surface.)

d) Factors limiting primary productivity in freshwater wetlands are not well understood, making it difficult to accurately predict the influence of nutrients, space, light, water, and temperature on created systems.

e) The limits to the assimilative capacity of freshwater wetlands for nitrogen are not known.

A broad range of factors contribute to nitrogen cyling in wetlands, and influence the treatment potential of created systems, by determining the forms and concentrations of nitrogen available within the system. These include wetland hydrology, concentration in inputs, and rates of immobilization, ammonification, nitrification, denitrification, and vegetative uptake and release (Chan, et al., 1982).

Two of the most important processes in nutrient cycling from the standpoint of stormwater and wastewater treatment capacity are nutrient accretion or burial in sediment and denitrification. Simpson (1983) noted that large amount of N appeared to be stored in the Delaware River tidal marsh sediments, despite the rapid decomposition of plant material in the fall. Lowry (1979) noted the importance of sediment sequestering in the Great Meadows marsh in Concord, Massachusetts. Studies in the Rhode River in Maryland (Jordan, in press, in Nixon and Lee, 1986) pointed to the large importance of mudflats in efficiently capturing forms of nitrogen released from a high marsh (100 percent of organic N, 100 percent of nitrite plus nitrate, and 49 percent of ammonia nitrogen).

Similar results were reported by Welsh (1980) for a higher salinity marsh-mudflat system in Connecticut. Reviewing findings in the northeastern states, Nixon and Lee (1986) pointed to the significant role that long term burial of wetland materials may play in loss of nutrients and contaminants. Based on studies reviewed, they proposed a rough general estimate of N loss due to sediment burial of 2.5 g N per sq. m. per yr. Jordan (1991, in press) has expressed confidence in 10 g N/sq. m. per yr., based on his recent field measurements.

Kadlec (1978) and others have argued that denitrification is the most important nutrient processing function of wetlands, yet, as previously discussed, most reported denitrification rates are based upon findings under extremely favorable laboratory conditions, and should be viewed with extreme caution (Jordan, 1991 in press). Field measured net denitrification rates in Sippewisset Marsh on Cape Cod (Kaplan, et al.,1979) were found to be 12 g N per sq. m. per year for tall S. alterniflora; 4 and 21 g N per sq. m. per year for emergent short

S. alterniflora marsh and salt flats respectively, and 22 g N per sq. m. per year for submerged creek bottoms. The rough average rate from all component marsh types generally equalled measured groundwater nitrate inputs.

Jordan (1991, in press) reviewed a number of studies in which denitrification rates were estimated as potentials or were measured in the field. He concluded that, even when unrealistically high measures of "potential" were eliminated, wetlands still showed great promise in removal of N via denitrification--on the order of 300 g N/sq m./yr., and via accretion (burial) at roughly 10 g/sq. m/yr. Favorable conditions for denitrification can be created in artificial wetlands.

Treatment Contribution Offered by Existing Natural Wetlands

In the Long Island Sound watershed, nutrient buffering contributions of salt water marshes, freshwater tidal marshes and riparian wetlands and floodplains are likely to be important, although an assessment on a sound-wide basis would be difficult to achieve given existing data. Nutrient processing capacities should be evaluated on a sub-watershed basis, as different types of wetland systems perform distinct buffering functions.

Production in natural coastal marshes appears to be nitrogen limited. On an annual basis, coastal marshes serve as slight net exporters of nitrogen, in which tidal waters carry a variety of N compounds to nitrogen-poorer adjacent waters (Teal and Valiela, 1978). Nitrogen losses occur primarily through this tidal exchange, and through denitrification, such that the two outputs compensate for inputs. Nevertheless, the antagonistic processes of the nitrogen cycle serve to biologically damp the alteration within the marsh which would otherwise result from changes in N inputs from terrestrial and atmospheric sources. Increases in nitrogen supply enhance primary production, decomposer activity, and secondary production, inducing changes in the physical structure of the marsh which allow predators to take advantage of increased food availability (Valiela and Teal, 1979). Several actions important to nitrogen cycling in freshwater and brackish wetlands, including nitrification, depend strongly on periodic aeration of the substrate, suggesting that alteration of natural tidal systems may inhibit key buffering functions.

Upstream riparian wetlands, floodplains, and bogs may have significant benefits in nutrient processing. Hemond (1983) found a riverine bog in Concord, Massachusetts to uptake 71 percent of total N on a mass balance basis. (Such nutrient starved systems, it should be noted, have been found to be altered in character by sustained nutrient loadings.) Lowry (1979) found average annual nitrate removal efficiencies of 20 percent in the Great Meadows marsh in Concord, Massachusetts, and up to 89 percent removal at the mid-growing season. Even in wetlands associated with small tributary streams and creeks, riparian zones are important in sequestering nutrients for use in stream systems by upstream biota, reducing discharge to downstream receiving waters.

Vegetated riparian buffers, many of which are underlain by wetland soils, have been found to attenuate pollutants in surface water and shallow groundwater via physical, chemical, and biological processes. Pollutants are filtered out by soils and plant materials, and interact with the inorganic and organic constituents of soil. Biological processes are also significant: nutrients are taken up by plants, and microorganisms process nutrients, heavy metals, and organic chemicals. Microbial processes may be extremely important. However, seasonal variations in buffer effectiveness are critical. Uptake processes may be greatly slowed during winter and early spring conditions (when snowmelt runoff may be highly contaminated), and contaminants taken up by buffer vegetation may be re-released in the fall or at plant die-off. Microbial activity is less affected in winter (Groffman, et al, 1990).

In groundwater, the extent of N removal in vegetated buffers depends upon several factors, including the N species at issue, groundwater flow patterns, depth of the root zone, contact time in the buffer substrate, the soil's acidity and organic content, the chemical oxidation state of the soil constituents, and the buffer vegetation type. Wetland soils may be highly efficient buffers for N in surface runoff and very shallow contaminant plumes. Chemical and biological processes are important. Wetland soils tend to be high in organic matter, depths to groundwater are shallow, allowing for better vegetative uptake, and microbial processes may be enhanced, depending upon acidity (Groffman et al, 1990).

For treatment of nutrients in surface runoff, including discharge from subsurface drains, the buffering effectiveness of riparian areas depends upon slope, the type of vegetative cover in place (forest and grass type), the density of vegetation, and the condition of the buffering zone itself. Studies in the Hunt-Potowomut watershed in Rhode Island revealed that up to 100 percent of nitrate could be removed from runoff in the peak growing season, depending upon various factors. Sheet flow is extremely important. Slopes exceeding three to five percent tend to be quite vulnerable to channelization, which may virtually eliminate nutrient processing functions (Groffman et al, 1990; Myers, 1989).

To perform these surface runoff treatment functions, buffers should be vegetated appropriately, and must be managed to prevent channelization (by regulating percent slope and access). Nutrient or contaminant-enriched plant materials may be harvested and should be properly disposed of.

The ability of wetland soils to remove nitrates and other contaminants from groundwater is highly dependent upon site-specific conditions, and may be limited, because contaminants frequently travel at depths beneath the zone where soil treatment and plant uptake can be achieved.

Every effort should be made to ensure that riparian and shoreline buffers are actively protected, and that the natural buffering capacity of watersheds is preserved. It may be possible to take better advantage of existing buffering capacity through selective retrofits of existing drainage systems, pretreatment of existing stormwater flows to wetland buffers, or use of managed vegetated buffer strips on a broad scale. However, wetland buffers are valuable habitats, vulnerable to channelization, sedimentation, and excessive nutrient or contaminant loading. They should generally be considered as a supplement to other treatment or source control practices (Myers, 1989).

Evaluating Wetlands as Nutrient Sinks; Examining the Need for Harvesting Biomass

Wetlands may serve as nutrient sources (e.g. through nitrogen fixation, lowering of pH); sinks (e.g. via denitrification, cation exchange, volatilization, biological uptake); or transformers (conversion of particulate to dissolved forms or vice versa, reduction of oxidized forms, etc). Concerning natural wetlands, Elder (1988) summarizes:

> " in very few, if any, situations does a wetland function as a true sink for nutrients and other contaminants. It is more likely to have a multiple role as a source, sink, and transformer, depending on the location, season, and innumerable environmental factors."

The degree to which created wetlands may be viewed as sinks depends upon the system design, the management and maintenance regime in place, and other factors. Investigators agree that hydrology is extremely important, but there is a lack of consensus regarding removal of enriched sediment and biomass.

Changes in water levels and duration of flooding may resuspend sediments and flush out enriched plant material and debris, and associated contaminants. Particularly for stormwater treatment, sediment forebays and/or pretreatment ponds are essential to prevent excess sedimentation, and should be calculated into projections of land requirements. Dredging enriched sediments from wetlands may resuspend contaminants, although dewatering should mitigate this concern, and can be easily accomplished in compartmentalized wetlands. Progressivily anaerobic sediment conditions (which may result from dense rhizome growth in Typha sp. for example) may induce the release of metals sequestered in sediments (RIDEM, 1989).

Considerable debate surrounds the issue of harvesting wetland vegetation at the end of each growing season to physically remove constituents taken up by plants. Findings have been quite variable with respect to the effectiveness of harvesting. Sloey, et al. (1978) determined that "only 5 to 20 percent of the nutrients detained by a wetland are generally stored in harvestable plant tissue" (p. 334). Similarly, Wile et al. (1983) stated that only eight to ten percent of the annual nitrogen and phosphorus loadings to the Listowel created wetland could be removed by harvesting. Other authors (Black, pers. com. in Lowry, 1979) found no discernable difference in discharged water quality with or without harvesting.

These observations are consistent with the fact that emergent wetland plants translocate a large percentage of above-ground nutrients to below-ground rhizomes and shoots prior to seasonal senescence. Because these constituents are not available to be leached from the system, the effectiveness of harvesting is reduced (Prentki, et al, 1978).

Pope (1981) found harvesting to be detrimental, in that abnormal root growth occurred which could potentially disturb flow and clog the wetland system. EPA guidance (1985) advises that harvesting of plant biomass is unnecessary in created wetland systems since a significant portion of the biomass is in below-ground growth. The significance of plant litter in adsorption and filtration processes throughout the fall, winter, and early spring has also been noted as limiting the advisability of harvesting. Where pretreatment facilities are in place, they will serve as sinks for many constituents.

Despite some uncertainty surrounding its benefits, harvesting is strongly encouraged, or required as a maintenance plan component in many jurisdictions where removal of nutrients in biomass is considered to be important in preventing release of nutrients or other contaminants that could otherwise cause exceedence of threshold concentrations.

II USE OF ARTIFICIAL WETLANDS FOR TREATMENT OF URBAN STORMWATER

Background

Within the past few years interest has grown in the use of created wetlands for treatment of stormwater runoff, due to an increasing level of knowlege regarding wetland processes, development of experience with use of wetlands for wastewater treatment, and heightened interest in the use of "natural" treatment methods which could offer habitat and aesthetic benefits.

Despite the complexity and ecological sensitivity of wetland systems, carefully designed and managed systems have provided degrees of urban runoff treatment comparable to that of more conventional stormwater treatment facilities or chemical treatment plants at significantly lower cost (Lakatos and McNemar, 1987). Of a survey of wetlands experts and stormwater management professionals conducted in 1986, 78 percent favored the use of created or reclaimed wetlands for stormwater treatment, 61 percent of whom cited the effectiveness of wetlands for pollutant removal (Lakatos and McNemar, 1987)

Wetlands process N in stormwater via the mechanisms described in Part I: through physical, chemical and biological means. Emergent wetland vegetation filters and impedes stormwater runoff flow, reducing velocity and promoting sedimentation. Sedimentation is important in removing particulate forms of N (Chan, 1982). Ammonium may be adsorbed to sediments, where it is biologically available, and may be removed from the system through volatilization, as is the nitrogen gas resulting from microbial denitrification processes in wetlands.

Wetland plants take up dissolved nitrogen forms directly from the water column via submerged roots, stems, shoots and leaves, and from the sediment via the rhizomes, roots and buried plant parts. Nutrients are translocated through the plant vascular system on a seasonal basis. Other mechanisms of storage in wetland vegetation include differential uptake of trace contaminants and immobilization in plant litter zones. Plants also serve as sites for microbial activity above and below the sediment surface (Kadlec and Kadlec, 1978; Chan et al, 1982).

Seasonal variation in assimilation capacity is an important factor in evaluating management needs. Although nutrient assimilation in artificial wetlands has been documented to be very efficient during the growing season, N is believed to be translocated into the water column, litter layer, rhizomes and sediments at vegetation senescence in the fall (Chan, et al, 1982; Lowry, 1979). N may subsequently flush or leach out of litter, where it is available to receiving waters. Studies as far south as north Florida have documented significantly decreased plant uptake rates during the winter months (Livingston, 1988). "First flush" volumes of stormwater may need to be diverted to other treatment facilities or stored for later treatment in wetlands.

State of the Art

Comprehensive assessments of literature on the use of wetlands for stormwater treatment have been prepared by a number of authors, including Stockdale (1986), Strecker, et al. (1989), and the State of Maryland (1987). An updated bibliography has recently been prepared by Stockdale (1991). Lakatos (1987), RIDEM (1989) and Chan (1982) reviewed the role of wetlands in stormwater pollution management, considering the reported effects of natural wetlands as well as those of wetlands constructed for pollution treatment.

These reviews summarize data on influent and effluent water quality, system effectiveness, flow and volume considerations, appropriate wetland size as a function of watershed area, and the biological characteristics of the systems. A full scale feasibility study on applicability of created wetlands technology to Long Island Sound hypoxia management should carefully consider the detailed data presented in these comprehensive reviews. It should be noted that a review of the literature did not reveal use of created saltmarsh wetlands for stormwater treatment, although a brackish enhanced natural marsh is in use in California.

Reported N Removal Efficiencies

Because created wetlands have only fairly recently been developed solely for the purpose of stormwater quality enhancement, much of the data that has provided a foundation for estimating N removal efficiency in system design has been derived from studies of wastewater renovation systems, dual purpose systems, or natural wetlands which have employed a range of experimental techniques. Unfortunately, fewer systems have been monitored for N removal effectiveness than for removal of suspended solids, organic loads, metals, and particulate P. Direct monitoring data on dissolved nitrate removal is scanty.

In addition, the created wetland systems cited in the literature are widely dispersed geographically and were designed to accommodate site specific variations in hydrology and stormwater characteristics. A wide variety of vegetation has been present, or has been planted for treatment of specific pollutants. The broad ecological variation among and within wetlands should also be considered in extrapolating from data on existing systems to predict potential treatment efficiency in the Long Island Sound basin.

This being said, reported treatment values for N species are encouraging, and are a reflection of these systems' effectiveness in treating dissolved N species. Strecker, et al. (1989) reported mean removal efficiencies for several N species (among 13 created wetlands around the U.S.) of 24% for TN, 14% for TKN and organic N, 31% for ammonia and 33% for nitrate. For an enhanced natural wetland managed to treat stormwater runoff from a variety of land uses in Minnesota, Willenbring (1985) reported 19 to 41 percent removals of TKN. Several other efficiencies have been reported for systems in the northern U.S. Sherger and Davis (1982, in State of Maryland, 1988) reported removals of 9% TKN and 56% nitrate from a natural wetlands in Michigan receiving stormwater runoff.

A compex wet detention pond-created wetland system treating runoff from a shopping mall in Massachusetts allows for a lengthy residence time (9 to 20 days for the average storm), and is both heavily vegetated and carefully protected from sedimentation. The system was designed using a model based on NURP data, which predicted 40 to 70 % total N removal (Daukas, Lowry, and Walker 1988). This relatively complex system is of particular interest, in that it lies within a water supply watershed (requiring monitored compliance with an NPDES permit). The dual purpose system controls peak flow (up to the 100 yr 24 hr event) using detention ponds and attenuates stormwater pollutants using created wetland technology. Runoff is directed to two created wetlands systems (totalling 1.86 ac.) to accommodate flow from upper and lower catchment areas. Flow is pumped to the upper wetland.

Performance of wetland stormwater treatment systems depends on hydrologic conditions, specific wetland and runoff characteristics, and other design and maintenance issues. Several authors have reported enhanced N removal efficiencies with increased detention time, reduced hydraulic loading, higher ratios of wetland area to tributary drainage area, and effective pretreatment and sediment removal. These findings reinforce the importance of maintaining conditions that promote biological activity and maximize stormwater contact with vegetation and the soil substrate (consistent with descriptions of removal mechanisms summarized in Part 1).

For example, Willenbring (1985) examined six dissimilar wetland treatment systems applied to lake restoration and found that percent TKN removal was more than twice as high in a treatment wetland having a ratio of tributary drainage area to wetland area of 16.5 and a low hydraulic loading rate, as compared to other systems which were smaller compared to the drainage area and had received higher hydraulic loadings.

Created wetlands have come into increasing use in Florida for stormwater and wastewater treatment. Although higher annual removal efficiencies clearly reflect the longer growing season, data from temperate North Florida may be instructive. Livingston (1988) reported 75 % removal of both Notal N and nitrite and 70 % removal of nitrate from a detention pond-artificial wetland system treating stormwater from a mixed commercial, residential and highway watershed in Tallahassee.

A complex fresh/brackish detention-wetlands system has been in place in Fremont, California since the mid-1980s. The "Demonstration of Urban Stormwater Treatment" (DUST) marsh consists of several cells, lagoons, and marshes in three systems, and has been effective in reducing suspended solids and inorganic nutrients, among other stormwater constituents. Since most storms occur during the winter, removal of dissolved N species by plants was less effective (Meiorin, 1989 <u>in</u> Hammer, 1989)

The State of Maryland implemented an aggressive stormwater management program in the early 1980's, and requires use of stormwater treatment systems employing a shallow permanent pool whenever possible. Maryland and Delaware have established design guidelines for use of constructed wetlands. N removal efficiencies of 30 to 40 percent have been consistently reported for carefully designed mature systems (in place 5 years) in Maryland and Delaware (E. Shaver, pers. com., November, 1991).

Of particular interest has been Maryland's program to retrofit existing detention facilities (installed for peak flow attenuation) to promote the significantly greater benefits of wetland treatment. In Prince George County, a 0.4 hectare dry pond was converted to a shallow wetland in 1987 to serve a 40 ha commercial watershed, improving its removal efficiency (Shaver, pers. com.). In the Long Island Sound watershed, a number of the many dry detention facilities and recharge basins in use might be suitable for retrofitting to extended detention ponds, wet ponds, or wetlands (Myers, 1989).

Issues for Consideration in Evaluating Applicability to Long Island Sound

The evaluation of created wetland technology for stormwater treatment in the Long Island Sound watershed must consider numerous important inter-related factors. In general these constraints include: availability and cost of land for treatment, pre-treatment, and control of damaging storm flows; proximity of available land to stormwater flows requiring treatment (and/or feasibility of altering flow patterns); seasonal variability in treatment efficiency; time required for treatment wetlands to reach full treatment potential; potential for mosquito breeding; potential need for a contingency in case of temporary system failure. Key issues are discussed in the following sections.

a) Appropriate Hydrology and Hydroecology. Understanding the relationship between treatment objectives and wetland hydroecology is essential in order to design treatment systems that will perform consistently over time. The source of runoff, velocity, volume, renewal rate, and frequency of inundation, among other factors, determine the chemical and physical properties of the wetland substrate. These factors, in turn, shape the character and vitality of the wetland ecosystem as reflected by species composition, primary productivity, nutrient flux, and organic deposition and flux. Establishment of the hydroperiod ultimately determines the form, nature and function of a wetland (Livingson, 1988). Full denitrification potential may only be realized when an anaerobic sediment-water interface has had time to mature (Shaver, E., pers. com., November, 1991).

b) Protection from Storm Flows, Flushing, and Scour. Many successful designs incorporate separate sedimentation basins for removal of heavy sediment and hydrocarbons, and detention facilities for diversion of large storm flows which could seriously disrupt wetland vegetation and resuspend contaminants.

c) Consideration of Tidal Influence. Complicated issues attend development of created wetlands in areas influenced by tidal action, including influence on hydraulic detention time, potential inundation and influence of storm surge, flow sequencing requirements, erosion protection needs, and particular construction and grading challenges experienced in salt marsh construction (Lowry, pers. com. 1991).

d) Suitability of Vegetation. Climatic factors, pollutant types and load, watershed and wetland hydrology, surrounding vegetation types and land use, and other factors all influence the survival and treatment performance of created wetland vegetation (RIDEM, 1989).

e) Nutrient Loading Rate. Although wetlands can accommodate enrichment of vegetation, excessive mass loading rates have been found to impair function. Nichols (1983) summarized the percent removal of N and P in a variety of high efficiency, managed wetlands receiving nutrients from sewage and runoff, and found that when total N inputs were held below roughly 100 kg/ha/yr of wetland per year, removal efficiencies exceeded 70 percent. Removal efficiencies fell rapidly at higher loadings. Athanas and Shaver (1987) projected N removals of 30 to 40 % for a created wetland receiving 700 kg/ha/yr. Shueler (1987) recommends an upper limit for N loading of 225 lbs/ac/yr.

f) Seasonal Variation in Function, and Re-release of Nutrients. Numerous authors have described the processes by which wetland plants assimilate nutrients, metals, and organic contaminants during the growing season and store or release them as plants senesce in the fall (Sargent, 1985; Stockdale, 1986; Chan, et al., 1982; Lowry, 1979). Salt marsh systems have been found to exhibit approximately equal uptake and release, on a yearly basis (Valiela and Teal, 1979). During the fall, and particularly in spring, floodwaters leach nutrients from decomposing plant matter and litter, and flush organic N to adjacent receiving waters. Freezing promotes release of N from plants and soils, making it available for release with snowmelt (Chan, 1982). As outlined in previous sections, sediments may be more important than plants in long-term nutrient capture.

Metals and organic chemicals are also stored and released, in patterns which appear to be specific to the chemical involved (Strecker, et al.,1989). Release of these contaminants as a potentially toxic "slug" may be of concern.

Discharges of waters rich in nutrients or leached contaminants can be controlled to some extent through harvesting of plant biomass (see discussion in Part I). Harvesting also serves to renew the vegetation's ability to remove nutrients via new growth. Harvested materials have been used as mulch, for fertilizer, and for use in construction of furniture and other materials. Woody stem growth has been found to be a more permanent sink for nutrients, requiring less frequent removal (Groffman, et al., 1990).

Area and Configuration.

a) Area. Unless extended detention for 24 hrs for the 1 yr storm is provided, wetland surface area should constitute at least 2 to 3 percent of the total area of the catchment area. Several successful systems cited previously (e.g. Emerald Square Mall in Attleboro, MA; DUST Marsh, Fremont, CA; systems in Florida and Maryland) provide for longer detention periods of several days to 3 or 4 weeks. The State of Florida requires that the first one inch of runoff be treated, and requires a minimum residence time of 14 days, while Delaware recommends 12 to 14 days. Expressed in terms of volume, a detention time of 24 hours for the 1 yr storm has been recommended to enhance pollutant removal and to allow the storage volume to be recovered prior to the next storm (State of Maryland,1987; Livingston,1988).

It is extremely important that sufficient area be provided to allow for conditions appropriate to the degree of physical and chemical treatment needed and for vegetative propagation (which has been found to require at least 75 percent shallow zones). Although wetland plant species have specific depth requirements, 6" is probably optimal (for vegetated areas of the system) for most species currently used in wetland treatment in the northeast (Schueler, 1987).

b) Hydraulic Loading. As stated previously, nutrient uptake has been found to be most effective where floodwaters flow slowly and evenly over the substrate, such that maximum contact with plants and with the sediment-water interface is provided (Chan, et al., 1982). Hydraulic loading rates of no more than 1 to 2 inches per week have been recommended by the State of Florida for wastewater treatment in natural wetlands. For stormwater management, Florida regulates the discharge rate, requiring that the total treatment volume may not be discharged in less than 120 hours, and that no more than half the treatment volume may be discharged within the first 60 hours following a storm.

c) Configuration. A 3:1 length to width ratio is recommended to maximize the flow path and prevent short-circuiting.

Other Considerations in Evaluating Applicability

Wetland treatment of stormwater offers a range of benefits. In communities in which liability concerns have created resistance to the use of wet detention, created wetlands may be more acceptable. Created wetlands managed for stormwater treatment in parks in Orlando, Florida, for example, have become valued recreational amenities (Livingston, 1988). Wildlife and habitat benefits of created wetland systems were almost unanimously cited in the studies examined. Created wetlands established at schools in Maryland were designed to meet educational and research objectives and have proven to be highly effective outdoor laboratories.

Despite these advantages, some fundamental limitations and constraints must be recognized. These include: proximity of available treatment sites to sources of runoff requiring treatment; feasability of rerouting drainage systems to provide appropriate flow characteristics for wetland treatment; availability of land for pretreatment; seasonal variability in treatment effectiveness; seasonal and variable nature of stormwater flows and potential for adverse flooding, flushing or dessication of wetland vegetation and sediment; potential release of sequestered contaminants in a large storm event; length of time required for wetland to "mature" in terms of nutrient processing capability; potential for mosquito breeding or other nuisances, and (in some areas) a degree of concern with regard to liability and/or exposure of wildlife and pets to elevated concentrations of contaminants in treatment wetlands (Chan, et al., 1982).

Management practices have been developed to overcome, or largely mitigate, these limitations, and to enhance the pollutant removal capabilities of created wetlands. These include inflow-outflow regulation, water level manipulation, flow distribution, seasonal storage, and a variety of biological mosquito control techniques. Benefits, constraints and mitigation measures must be carefully weighed in a feasibility analysis.

Candidate Areas for Wetland Creation

Areas that might be considered by the LISS for establishment of created wetlands for stormwater treatment include highway medians, parklands, underutilized waterfront areas, and industrial and commercial "campuses" in the upper portion of the Sound watershed. Use of wetlands in highway medians for de facto treatment of stormwater has a long history in Florida, has been tested in Maryland and proposed in Rhode Island, and has recently been suggested by Jordan (1991, in press) for application in the Chesapeake basin. The treatment effectiveness of riparian buffer zones could also be enhanced. In addition, numerous dry detention basins in the watershed, developed for flood control purposes, may be suitable for upgrading to wetlands, extended detention basins, or wet ponds (Myers, 1989).

Summary

Evidence from urban or urbanizing areas having a similar land-use mix to that of Long Island, Westchester County, and the Connecticut shoreline suggests that well-planned and carefully designed created wetlands may offer considerable potential as a flexible, low-cost technology for treatment of a range of stormwater contaminants, including N species. Removal of between 40 and 70 % of N input concentrations can be expected on a year-round basis, with removal efficiencies of 70 % or greater being likely in the growing season. Removal may be permanent (via denitrification and/or burial in sediment) or may vary on a seasonal basis, in which highest temporary removal rates coincide with summer periods of seasonal hypoxia. Created wetlands offer a range of benefits in addition to water quality enhancement.

On a sub-watershed basis, created wetlands (and other water quality best management practices) should be incorporated into an overall stormwater master planning strategy that considers the optimum means of dealing jointly with flood hazard and water quality management needs for both developing and urbanized areas. Pretreatment and proper maintenance must be provided.

III USE OF CREATED WETLANDS FOR TREATMENT OF WASTEWATER

Background

Constructed wetlands are coming into widespread use throughout the U.S. as a low cost means of providing final wastewater treatment and upgrading muicipal and individual waste disposal facilities. Results of a survey conducted for EPA by Sherwood Reed and Donald Brown indicate that 154 municipalities in the U.S. use constructed wetlands as a component of their wastewater treatment strategy. In many areas constructed wetlands are relied upon for complete wastewater renovation. Constructed wetlands currently in use vary in size from 10,000 gpd in El Dorado, New Mexico, to 20 mgd in Orlando, Florida (Small Flows Clearinghouse, 1990).

Roughly one third of the municipal constructed wetlands identified by Reed and Brown are free water surface wetlands, while 98 are subsurface flow wetlands. Several communities use both types in series. Free surface wetlands have a water surface open to the atmosphere, have an impervious or semi-impervious bottom, and are planted with emergent rooted vegetation. They include several variant sub-types: marshes, marsh-pond systems (marsh followed by a pond), pond systems (planted with clumps of vegetation), and seepage wetlands (wastewater irrigated fields overgrown with volunteer emergent wetland vegetation as a result of intermittent ponding and seepage of wastewater).

Subsurface flow wetlands were pioneered by the Max Planck Institute in Germany and have been in use in Europe for some time. They consist of shallow beds or trenches filled with permeable rock, sand, or gravel media, or underlain with peat, in which plants are rooted. A layer of dry media covers the top surface of the bed or channel. Wastewater does not come into contact with the surface, but instead flows through the permeable media at a depth of several inches from the surface.

Cost variations among the two types of constructed wetlands are complex. The average wastewater flow applied per acre to a subsurface flow wetland is roughly seven times greater than that applied to free water surface wetlands, yielding a capital cost per gallon of wastewater treatment capacity for a subsurface flow wetland that is roughly half that of a free water surface wetland. (However, see subsequent discussion of the effects of loading rate on N removal effeciency.)

The average subsurface flow wetland is about three acres in size, treats 483,000 gpd., and was build at a cost of 53 cents per gpd. Capacity varies from 10,000 to 3,500,000 gpd. However, the average reported construction cost of subsurface flow wetlands is $87, 218 per acre, or roughly four times as costly per sq. ft. as free water surface wetlands, which can be built for an average of $22,000 per acre. Free water surface wetlands have been built at an average construction cost of 99 cents per gpd of capacity, with capacity varying from 60,000 to 20 million gpd. The cost of rock media introduces the large price difference (Small Flows Clearinghouse, 1990). (These cost differences do not consider upstream pretreatment.)

State of the Art

The U.S. EPA Risk Reduction Environmental Laboratory (REEL) in Cincinnati, OH recently sponsored a survey of the use of constructed wetlands for treatment of municipal and industrial wastewaters in the U.S. The survey evaluated many design parameters and investigated a range of factors influencing cost-effectiveness and reliability. When published, the full results should prove useful in evaluating the applicability of constructed wetland technology for wastewater treatement in the Long Island Sound watershed (Reed and Brown, unpublished manuscript, 1991).

Reed and Brown (1991), however, offer several general conclusions and recommendations. They state that the free water surface concept appears to offer a reliable and cost effective method for wastewater treatment, polishing and system upgrade, although these systems depend on a higher level of pretreatment than subsurface wetlands, and those with water deeper than 10 cm appear to show less effective ammonia removal. The authors state that subsurface flow wetlands also appear to be reliable and cost-effective when properly designed, although optimum treatment of certain constituents may be dependent upon improved oxygen distribution in the system bed.

Range of Systems in Use

In the 1950's, European investigators pioneered the use of constructed wetlands in treatment of industrial runoff and wastewater effluent (Seidel, 1976; Czerwenka and Seidel, 1976; DeJong, 1976 in Lowry, 1979). In the U.S., Brookhaven National Laboratories has been a leader in development of the technology since the early 1970's, as have the University of Wisconsin, the University of Michigan and universities in Florida (Fetter, et al., 1976; Spangler, et al., 1976, in Lowry, 1979).

Hantzsche (in Godfrey, 1985) reviewed the use and enhancement of natural wetland systems for wastewater treatment. These systems attempt to achieve wastewater treatment in a manner that minimizes ecological disturbance. Investigators in Florida have achieved high N species removals in cypress domes, hardwood swamps, and freshwater marshes. Enhanced natural wetlands have also been utilized in Wisconsin, New Mexico, Pennsylvania, and Michigan, in some cases with an objective of revitalizing degraded or drained wetlands. In spite of their demonstrated treatment capability, however, most jursidictions strongly discourage or prohibit use of natural wetlands for wastewater treatment, except under controlled experimental circumstances for rehabilitation of severely degraded areas.

The use of created wetlands has recieved much higher acceptance due to better opportunities for process control and reduced risk of adverse environmental effects. In general, constructed wetlands have fallen into two groups. Designers of the first type attempt to simulate a natural wetland, which is made to receive relatively low loadings of pretreated effluents for further polishing (e.g., Arcata, CA; Incline Village, NV; Harriman New York). This type may provide other wetland values.

Other systems have been designed to treat moderate to high loadings of wastewater in as small an area as possible (Santee and Gustine, CA; Collins, MS; Port Perry and Listowel, Ontario; and many European systems). Designers of the Listowel, Ontario, system have developed very successful strategies for constructed marsh treatment in cold climates (Black, et al, 1981; Reed, et al, 1984) as have investigators in Michigan. Large scale systems have been developed in several states, including Pennsylvania, Florida and Missouri. Large scale tidal systems are in use in California.

The broad range of strategies and treatment efficiencies reported have served to complicate the development of design standards. The State of Texas, which strongly encourages the use of created wetlands for wastewater treatment, has issued design guidelines for construction. Guidance is also available for the State of Florida, where many vegetative aquatic systems are in use.

A Note on Wetland-Aquatic Systems

Although evaluation of aquatic systems is beyond the scope of this research effort, several combined wetland-aquatic systems are in use in New England and represent a technology that may offer potential for application to the needs of Long Island Sound. An enclosed pilot system in Providence, Rhode Island (one third wetland and two-thirds aquatic; 16,000 gpd), consisently reduces combined ammonia and nitrate in influent from 10-20 mg/l to less than 5 mg/l. The system occupies roughly .25 acre and discharges to Narragansett Bay at Fields Point. Similar systems are in place for treatment of septage (Harwich, MA), boat waste (Marian, MA), and seasonal resort sewage flow (Sugarbush, VT).

Capital costs of these compact systems are low, although operation and maintenance costs may be significant due to sophisticated management requirements. Because the systems may be decentralized, portions of the raw wasteload from an overloaded plant may be pulled off line for treatment, preserving POTW capacity. Options for POTW remedial retrofitting may be significantly broadened. The systems may be maintained with minimal influent in a "recycling" mode during low volume seasons and scaled up for seasonal use (Sargert, S., Peterson, S., Petersen, J., personal communication, 1991). General sizing requirements for wastewater polishing in these wetland-aquatic systems (assuming shoreline effluent discharge) are provided in Table 3.

Findings Regarding Nitrogen Removal Performance

As is the case with the use of created wetlands for stormwater treatment, a great diversity of opinion exists among designers, researchers and operators concerning basic issues and evaluation factors. There is a lack of consensus as to the advantages of free water surface versus subsurface flow design, optimum system configurations, appropriate pretreatment requirments, acceptable hydraulic, organic and nitrogen mass loading rates, effluent disinfection needs, depth of water and media, optimum type of media, type and management of plant species, and other important considerations (Small Flows Clearinghous, 1990).

Similarly, many of the caveats discussed with regard to comparative evaluation of performance data for stormwater treatment systems apply equally to wastewater systems. Again, a lack of long-term performance data restricts evaluation of alternatives, systems and circumstances are highly variable, and a range of experimental methods have been used in monitoring results. Wastewater system performance is additionally complicated by the fact that many systems have been built as retrofits or "add-ons" to existng impaired facilities, such that performance may reflect pre-existing problems.

This being said, investigators have consistently reported very successful treatment of conventional pollutants such as TSS, BOD, metals, and bacteria. On the basis of a review of wetland wastewater treatment systems research, EPA Region V concluded that studies had "clearly shown that constructed wetlands provide a highly effective means of achieving either secondary treatment standards on a year-round basis or advanced treatment standards on a seasonal basis" (U.S. EPA, 1983).

Treatment effectiveness for nitrogen has been less consistent among the systems reviewed for this study, and appears to vary strongly between free surface and subsurface systems, and depending upon other factors such as effluent concentration, loading rate, availability of a carbon source, and vegetation type. In a comparative study, Bastian (1986) found a broad range of reported nitrogen removal efficiencies (40 to 90 %) among studies of natural and constructed wetlands receiving secondarily treated effluent.

With regard to free water surface systems, Wile et al., 1981, reported 80 percent nitrate removal efficiency in an artifical marsh in Ontario, while 50 percent nitrate removal was reported in an enhanced natural marsh in Wisconsin (Fetter et al,1978, in Boto and Patrick, 1978). A seepage wetland in Vermontville, MI, showed only 7.7 % removal of nitrate/nitrite, but 87 % removal of ammonia (Sutherland, 1979 in Lowry, 1979). For marsh pond systems at Brookhaven National Laboratories, Small (1978 in Lowry,1979) reported roughly equal removals of nitrate/nitrite (53%) and ammonia (58%).

Reed or gravel bed systems also show a range of removals. Nitrate removal of 47-59 percent was reported for a Max Planck vegetated gravel bed system in Wisconsin (Tourbier, 1981). Reviewing performance worldwide, Knight (1990) found typical TN removal efficiencies of 75 to 95 % for constructed wetlands receiving low to moderate mass loads, suggesting that mass loading rates are an important factor in effectiveness. Up to a mass loading of 10 kg/ha/day, TN removal efficiency was highly correlated with loading rates. At loading rates between 10 kg/ha/day and 80 kg/ha/day, TN removal efficiency varied widely, with some systems continuing to show high efficiency and others rapidly losing assimilative capacity (Knight, 1990).

Ammonia removals reported have been high, ranging up to 94% at the Santee, CA facility, with a mass loading rate of roughly 11 kg/ha/day. If other factors are not limiting, Knight (1990) states that removal efficiencies of 70 to 90 percent are typical. Efficiency is significantly decreased with short hydraulic residence times, high loading rates and low temperatures. For maximum ammonia removal efficiency, a minimum design hydraulic residence time of 3 to 5 days is advised. As with TN, a decrease in ammonia removal efficiency has been noted at loading rates above about 10 kg/ha/day (Knight, 1990).

Factors in N Removal Efficiency

As suggested in the preceding sections, many factors affect N removal efficiency, although the degree may depend upon the type of created wetland under consideration. Application (hydraulic loading) rates have proven to be an important, and controversial, variable. Gersberg et al (1983) found that reducing the application rate from 16.8 cm/day to 8.4 cm/day increased TN removals in mulch-amended beds from 60 % to 86 %. Very low application rates of 1.85 cm/wk in a system at Disney world showed 82 % TN removal without carbon amendment (Kohl and McKim, 1980). Wile, et al, 1985 (in Godfrey 1985) found a water load of 200 cubic m/ha/day (2 cm/day) to provide maximum treatment efficiency (up to 90 % removal of TN in a system receiving raw sewage).

Hydraulic loading rates of .36 cm./day have been recommended by Kadlec and Tilton (in Knight, 1990). Knight (1990) reported hydraulic loading rates between 0.7 and 50 cm/day, and stated that rates should not exceed 2.5 to 5 cm/day for FWS wetlands and 6 to 8 cm/day for subsurface flow wetlands. Very high hydraulic loading rates, although technically feasible, can yield mass loadings detrimental to treatment function.

Availability of a carbon source to drive denitrification has been shown to enhance N removal in both free surface and subsurface flow systems. Gersberg et al (1983) reported TN removals of 25 % in a subsurface flow bed in Santee, CA, without addition of a carbon source, and removals of 95 % with addition of methanol. When mulch was used as a carbon source at the same high application rate (16.8 cm/day) a 60 % TN removal was achieved. The authors found that even at extremely high application rates (102 cm/day), more than 95% total inorganic nitrogen removal could be attained by using a methanol to nitrate ratio of 4.5 or greater.

These authors conclude that if loss of biomass carbon during decomposition could be avoided (or if carbon could be converted to a form directly available to denitrifiers) more than the optimal carbon loading could be supplied. The authors advocate cutting and mulching the biomass in place as the simplest method of returning biomass carbon in a usable form to the wetlands, and as a means of ensuring optimum density of plant cover.

Long detention time (10 days) appeared to play a large role in the 95 percent TN removal reoported by DeJong (1976) for an artificial marsh in the Netherlands. The length of the growing season, long detention time and the variety of vegetation in place contributed to the 93 percent TN removal from secondarily treated wastewater reported for a Florida artificial wetland (Knight, 1985). Wile et al., 1985 (in Godfrey, 1985) found a 7 day detention time to be optimal for artificial wetlands, based on their long term research at Listowel, Ontario.

At a constant hydraulic loading rate, detention time is influenced by evaporation in summer and ice formation in winter. Wile, et al. (in Godfrey, 1985) found that evaporation during summer could exceed 60 % of the hydraulic loading rate, resulting in a significant increase in required detention time and lowered treatment efficiencies that reflected extreme reducing conditions.

As stated in Part II, a factor of key importance to wetland function is the hydroperiod. Hydroperiod tolerances for a range of wetland species have been determined, and should be considered in design to optimize plant uptake and cycling. Other important hydrologic and hydroecological issues include infiltration capacity, water balance, soil characterization, residence time, evapotranspiration rate, storage volume, measurement of background water chemistry, and other factors.

Area Requirments and Configuration Issues

Land requirements depend upon hydraulic loading rates, detention time, and other factors. Wile, et al, 1985, (in Godfrey, 1985) suggest that at the optimum loading rate of 200 cubic m/ha/day found at Listowel, a 1 mgd (3785 cubic m/day) community would require a 20 ha (50 acre) wetland plus additional land for pretreatment facilities. The authors point to the significant land savings over conventional treatment, for which 40 ha (100 acres) would be required for a seasonal discharge lagoon with 180 day retention. A range of other area reported area requirements are reviewed by Knight (1990).

Conceptual area requirements for renovation of effluent from Connecticut POTWs using free-surface wetlands are provided in Table 1. Table 2 presents conceptual land area needed to achieve LISS Level 2 and Level 3 TN concentrations at the same POTWs. Area requirements were developed for Table 2 using mass loading rates and treatment efficiencies reported at existing free-water surface and subsurface flow facilities by Knight (1990).

Area requirements must also consider the lifespan of the system. Kadlec (in Godfrey, 1985) describes the expansion over time of the saturated zone and the surrounding zone of rapid pollutant removal within a created wetland. The system must be large enough to ensure that over the life of the system the area is adequate to retain or process all of the pollutants. If area is insufficient, eventual breakthrough will occur. The authors suggest harvesting of plant biomass as a means of maintaining high removal rates indefinitely on a limited wetland area.

The need to provide for slow sheet flow through the system, even internal distribution, and a high length to width ratio (3:1) to prevent short-circuiting (in FWS wetlands) has also been stressed by a number of authors (Kadlec, in Godfrey, 1985; Knight, 1990). Using a number of cells in series has become routine, to ensure even distribution of flow, maintenance of plant communities, flexible rotation, and ease of maintenance. Newer created wetlands are frequently designed with multiple input points to a single cell.

Note on Potential of Created Tidal Marshes

Although this review did not reveal instances of the creation of artificial saltwater tidal marshes for wastewater treatment, tidally influenced systems are in use in southern California, and impacts of long-term discharges to natural tidal systems have been studied. Studies of the Tinicum Marsh and other Delaware River marshes in the 1970's were instrumental in drawing attention to the role of wetlands in mitigating adverse water quality impacts (McCormick, Grant, and Patrick, 1970; Simpson, et al., 1978).

Several research efforts in the Sippewisset Marsh on Cape Cod, conducted by Valiela, Teal, and others, have demonstrated the potential effectiveness of salt marshes for wastewater treatment, due to their high productivity and efficient nitrate cyling (Valiela, Teal, and Sass, 1973). Of particular note is the finding that additions of ammonia reduce nitrogen fixation rates, thus dampening a source of N production (Valiela, et al, 1976). The complexities surrounding construction of systems in tidal areas were briefly discussed in "Applications to Stormwater Managaement."

Siting Considerations of Importance in Long Island Sound

Siting created wetlands to address a portion of the wastewater treatment needs of the Long Island Sound Watershed would involve a number of important tasks. The first task would be to determine the level of treatment desired for specific facilities, and the critical time period within which N, as a wastewater constituent and as a stormwater constituent, should control specific design factors for average and peak flow. Treatment strategies would likely involve a mix of technologies used in various combinations during different seasons.

Hydrologic and hydraulic constraints would be of primary concern in evaluating use of created wetlands technology, although systems have been constructed in many upland areas where uniform grades of less than 5 percent can be achieved. Other issues which would limit applicability, increase siting complexity, or increase costs include:

1) presence of outside influences from other sources of contamination (point or non-point sources) which would impair the functioning of the system, especially during storm flows;
2) presence of public or private water supplies which might be influenced by the facility;
3) presence of rare or endangered species of plants or animals in or near a candidate area;
4) presence of a hydrologic or hydraulic system that would limit the feasibility or effectiveness of created wetlands technologies;
5) unfavorable climatic conditions;
6) lack of available data with which to make responsible predictions as to system function and feasibility;
7) lack of available land area for pretreatment;
8) lack of resources for responsible design, management, and monitoring;
9) public resistance

A cost-effectiveness determination would be required to evaluate whether created wetlands could compare favorably with BNR or other advanced nutrient removal techniques as a means of achieving a portion of nitrogen removal requirements in the Sound. To determine cost feasibility on a plant-by-plant basis, an "economically feasible distance" would need to be calculated for each plant, considering costs of gravity transmission, distribution, and land acquisition. Land within a radius described by this distance could then be considered for further evaluation. The amount of acreage required would depend upon the technology or mix of technologies chosen and constraints at issue on available sites. Political factors and public acceptance would also require careful evaluation prior to investment in detailed evaluation of candidate sites.

Summary

Constructed wetlands appear to offer potential for polishing treatment of a portion of the Long Island Sound's POTW discharges, or for full treatment where flow might be taken off-line to preserve individual plant capacity. Even considering costs for land acquisition and re-distribution of flow, cost-efficiency benefits appear compelling, based on evidence from free-water surface and subsurface flow systems in climates similar to that of the Long Island Sound watershed. Nitrogen removal efficiencies depend upon system type, numerous tehnical design and management factors, and N species considered, but have been reported at ranges between 60 and 95 % for many systems.

Despite their higher construction cost, subsurface flow wetlands may offer greater potential than free water surface systems in this watershed, particularly in densely populated areas, due to their greater cold tolerance and potentially higher treatment capacity. Creation of salt marsh treatment systems appears to be technically difficult, particularly for high marsh situations, although natural and enhanced tidal systems have been shown to be highly effective for nutrient removal. Combined wetland-aquatic systems also offer potential for disaggregated treatment of a portion of the flow from POTWs nearing capacity.

TABLE 1.

CONCEPTUAL LAND AREA REQUIREMENTS: POLISHING TREATMENT FOR CONNECTICUT POTW DISCHARGES: FREE WATER SURFACE CONSTRUCTED WETLANDS [1]

Plant	**Design Flow** (mgd)	**Salt Marsh** [2] (acres)	**Freshwater Marsh** [3] (acres)
Branford	4.5	400.5	468
Bridgeport E.	12.0	1068	1248
Bridgeport W.	30.0	2670	3120
Fairfield	9.0	801	936
Greenwich	12.5	1112.5	1300
Milford, B.Bk.	3.1	275.9	322.4
Milford, Hous.	8.0	712	832
New Haven, E.	40.0	3560	4160
Norwalk	15.0	1335	1560
Stamford	20	1780	2080
Stratford	11.5	1023.5	1196
West Haven	12.5	1112.5	1300
Westport	2.9	258.1	301.6

[1] Marsh area required to renovate one MGD of typical secondary effluent, having a TN concentration of 18.2 mg/l. Adapted from Stanley, Associates, Inc.

[2] For N salt marsh treatment, 89 acres at 622 lbs/yr/ac derived using the following formula:

$$1 \text{ MGD} \times 18.2 \text{ mg/l} \times 8.34 = \frac{151.8 \text{ lbs./day}}{89 \text{ acres}} \times 365 \text{ days/yr}$$

$$= 622 \text{ lbs./yr/ac}$$

[3] For N freshwater marsh treatment, 104 acres at 533 lbs/yr/ac derived using the following formula:

$$1 \text{ MGD} \times 18.2 \text{ mg/l} \times 8.34 = \frac{151.8 \text{ lbs./day}}{104 \text{ acres}} \times 365 \text{ days/yr}$$

$$= 533 \text{ lbs./yr/ac}$$

TABLE 2.

CONCEPTUAL LAND AREA REQUIREMENTS: FWS AND SF CONSTRUCTED WETLANDS TREATMENT FOR CONNECTICUT POTW DISCHARGES: LEVEL 2 AND LEVEL 3 YEAR-ROUND TN CONCENTRATIONS [1]

Plant	Design Flow (mgd)	Level 2 (9mg/l) [2] (acres)	Level 3 (4mg/l) [3] (acres)
Branford	4.5	315.2	39.8
Bridgeport E.	12.0	840.3	106.2
Bridgeport W.	30.0	2100.7	265.3
Fairfield	9.0	630.3	79.5
Greenwich	12.5	875.4	110.7
Milford, B.Bk.	3.1	216.9	27.4
Milford, Hous.	8.0	560.2	70.6
New Haven, E.	40.0	2801	353.7
Norwalk	15.0	1050.5	132.6
Stamford	20	OK	88.4
Stratford	11.5	889.2	101.8
West Haven	12.5	875.4	110.7
Westport	2.9	203.0	25.7

[1] Land area required to renovate effluent of 18 mg/l TN (CT DEP reported average) to LISS mid- and high level management scenarios: Level 2 = 9 mg TN per liter year round; Level 3 = 4 mg TN per liter year round. Source: Status Report and Interim Actions for Hypoxia Management, LISS, 1990.

[2] For Level 2, requiring a 50 % reduction, a mass N loading rate of 2.4 kg/ha/day was used. This mass loading rate yielded 45% TN removal in a trench marsh (FWS) system in Listowel, Ontario. Source: Knight, R.L., 1990. Wetland Systems. Ch. 9 in S.C. Reed (ed.) Natural Systems for Wastewater Treatment. WPCF Manual of Practice FD-16. Acreage was derived using the following formula:

$$\text{Area (acres)} = \frac{(18\ \text{mg/l})\ (3.78\ \text{l/gal})(\text{MGD})(2.47\ \text{ha/ac})}{2.4\ \text{kg/ha day}}$$

[3] For Level 3, requiring a 78 % reduction, a mass N loading rate of 19 kg/ha/day was used. This mass loading rate yielded 88% TN removal in a subsurface system in Ingstrup, Sweden. Source: Knight, R.L., 1990, ibid. Acreage was derived using the following formula:

$$\text{Area (acres)} = \frac{(18\ \text{mg/l})\ (3.78\ \text{l/gal})(\text{MGD})(2.47\ \text{ha/ac})}{19\ \text{kg/ha day}}$$

TABLE 3.

CONCEPTUAL LAND AREA REQUIREMENTS: POLISHING TREATMENT FOR CONNECTICUT POTW DISCHARGES: SOLAR WETLAND-AQUATIC SYSTEMS [1]

Plant	**Design Flow** Mgd)	**Land Area Required** (acres)
Branford	4.5	10.4
Bridgeport E.	12.0	28
Bridgeport W.	30.0	69.3
Fairfield	9.0	21
Greenwich	12.5	29
Milford, B.Bk.	3.1	7.16
Milford, Hous.	8.0	18.5
New Haven, E.	40.0	92.4
Norwalk	15.0	34.3
Stamford	20	46.2
Stratford	11.5	26.56
West Haven	12.5	29
Westport	2.9	6.7

[1] Land area required to renovate effluent from secondary to tertiary quality (TN< 5 mg/l. year-round. Assumes shoreline or riverine permitted discharge; does not consider area needed for leachfield if inland treatment site is used. Source: personal communication, Susan Peterson, Ecological Engineering, Inc., November, 1991.

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Can Seaweed Farms Alleviate Hypoxia in Western Long Island Sound?

by

Valrie A. Gerard

CAN SEAWEED FARMS ALLEVIATE HYPOXIA IN WESTERN LONG ISLAND SOUND?

Valrie A. Gerard, Associate Professor
Marine Sciences Research Center, SUNY Stony Brook

SUMMARY

Seaweed farming has the potential to alleviate hypoxia in western Long Island Sound by reducing nutrient concentrations and microalgal production. To be effective, high seaweed biomass concentrations and production rates would have to be maintained over extensive areas, particularly during summer. Successful large-scale cultivation in other countries suggests that this is possible. Successful farming in western Long Island Sound, however, will require more than the straightforward adoption of Chinese or Japanese methodology. High temperatures preclude summer cultivation of the most promising species, *Laminaria saccharina*. Local species which grow well at summer temperatures do not have high sustained rates of production, are not suited for growth on artificial substrata, have no commercial value, or have not yet been tested and developed as crops. Development time will probably be on the order of a decade, and construction and operational costs will probably be high. Cultivation of a commercially valuable species, particularly for phycocolloid extraction, could offset costs. Loss of seaweed biomass from farms has the potential to cause much worse hypoxia than already exists in western Long Island Sound.

RATIONALE

Microalgal production, stimulated by enhanced nutrient input (particularly dissolved inorganic nitrogen, DIN), appears to a primary cause of hypoxia in western Long Island Sound. Particulate organic matter, consisting of phytoplankton and related detritus, sinks below the thermocline and increases the biological oxygen demand through microbial decomposition in the lower water column and benthos. The problem is greatest during summer, when microalgal production is not light-limited and when the water column is strongly stratified. Theoretically, production of large amounts of seaweed biomass on farms in western Long Island Sound could alleviate this problem. Seaweeds would compete with the microalgae for nutrients and light, thereby reducing microalgal production. The seaweed biomass would be removed by harvesting, reducing the total nitrogen and organic matter in the system. Production costs could be at least partly offset by commercial utilization of the seaweed biomass.

SUCCESSES AND FAILURES IN SEAWEED FARMING

Millions of tons of seaweed are produced on farms annually. In fact, current annual production of the kelp, *Laminaria japonica* (over three million tons wet weight), is greater than that of any other single aquaculture species. China and Japan are the main producers. Most of the kelp is used for food or for extraction of alginate, a phycocolloid (Brinkhuis et al. 1987, Tseng and Fei 1987). China and Japan also produce one half million tons of the red algae, *Porphyra* spp., on farms as a food crop (Tseng and Fei 1987). *Laminaria japonica* and *Porphyra* are grown on artificial substrates (ropes and nets, respectively), which are moored to the bottom in shallow, nearshore waters. Both of these seaweeds are domesticated and, in each case, control of the entire life-history of the plant is an important factor in large-scale production (Tseng 1984).

A third seaweed crop that is commercially farmed on moored nets consists of the tropical red algae, *Eucheuma* spp. *Eucheuma* is primarily produced in the Philippines and Indonesia for extraction of the phycolloid, carrageenan. These algae are not domesticated; seedstock are produced vegetatively by dividing larger plants, which makes their production labor-intensive (Doty 1979).

Seaweed farming has been less successful in the U.S., where most efforts were aimed at biomass production for energy, rather than for food or phycocolloids. The most promising species tested for biomass production was the west coast giant kelp, *Macrocystis pyrifera* (North 1987). A parallel study by the New York Marine Biomass Project (NYMBP) identified three candidate species: the kelp, *Laminaria saccharina*, a red alga, *Gracilaria tikvahiae*, and a green alga, *Codium fragile* (Brinkhuis et al. 1987). Field tests of the first two species in central Long Island Sound did not succeed in obtaining high biomass yields, largely due to site and species characteristics (discussed in detail below). The national Marine Biomass Program failed because it did not demonstrate the economic feasibility of using seaweed as a biomass crop in the U.S. Failure was attributable to the high technology approach, which was expensive and demanded rapid results, and to political problems, rather than to insurmountable biological problems. The Chinese are now cultivating *Macrocystis pyrifera* experimentally as an energy crop. Japanese-style production of *Porphyra* in Puget Sound (Mumford 1987) may be the first commercially successful attempt to farm seaweed in the U.S.

In addition to floating farms, coastal ponds or tanks have been used for commercial or experimental production of several seaweed species. Thousands of tons of the red algae, *Gracilaria* spp., are produced annually in brackish ponds in Taiwan for extraction of agar (Chiang 1981). The red alga, *Chondrus crispus* (Irish moss), which is commercially important for carrageenan production in North America and Europe, was experimentally grown in land-based tanks in Nova Scotia (Bidwell et al. 1985). This system was not profitable due to seasonally light-limited production, but was thought to have potential for more southern, sunnier sites.

BENEFITS OF SEAWEED FARMING IN WESTERN LONG ISLAND SOUND

Nutrient assimilation by seaweeds

Macroalgae take up dissolved inorganic nutrients (NO_3, NO_2,

NH_4, PO_4,...) over their entire surface. Uptake rates depend on the species and environmental conditions, including nutrient form, concentration, water motion, temperature, and irradiance. Many species are capable of luxury uptake which exceeds growth requirements, accumulate internal nutrient reserves and maintain high concentrations in their tissues.

The ability of seaweeds to act as a nutrient sink and reduce nutrient loads in closed systems has been demonstrated experimentally. *Gracilaria* grown in raceways and tanks provided the final step in biological tertiary sewage treatment in experimental systems at Woods Hole and the Harbor Branch Foundation (Ryther et al. 1979). *Gracilaria* and the green alga, *Ulva*, were used to take up ammonium in experimental closed system fish culture (Harlin et al. 1978). In both cases, the seaweeds were found to efficiently reduce DIN concentrations.

The use of seaweed farms to reduce hypoxia in western Long Island Sound depends partly on the ability of seaweeds to compete with microalgae for nutrients. Seaweeds are at a disadvantage in this competition. Microalgae have higher surface area to volume ratios and higher specific growth rates. They are transported within a water mass and, therefore, are able to deplete nutrients within that mass. The only conditions under which seaweeds can effectively compete for nutrients are when microalgal growth is limited by some other factor, such as light, or when a large amount of seaweed biomass is exposed to the nutrients "upstream" of the phytoplankton. Extensive seaweed farms could provide both conditions.

Potential nutrient removal by seaweed farms in western Long Island Sound can be estimated using production data from existing farms. Assuming a harvestable production rate similar to the average for *Laminaria japonica* farms in China (15 dry tons per hectare in the 9 month growing season from October to June) and the 3% nitrogen content characteristic of *Laminaria saccharina* grown under high DIN, a kelp farm in western Long Island Sound could remove 500 kg of nitrogen per hectare from the water over a 9 month period. The input of DIN to the western Sound estimated during winter 1970 was 50 tons per day (Bowman 1977) or 13,500 tons per 9 months. Theoretically, kelp farms covering 27,000 hectares (280 km^2), or 50% of the entire area of western Long Island Sound from the Throgs Neck Bridge to Eaton's Neck, could assimilate the total winter DIN input to the western Sound. Assimilation would not occur at a constant rate but would vary with biomass production, increasing exponentially as biomass accumulates following planting, and decreasing as growth becomes light-limited at high densities.

The same calculations can be made for a potential summer crop. The average harvestable yield of a Japanese *Porphyra* farm is 4-5 dry tons per hectare per year (Mumford 1987). The yield is low in comparison to kelp farms primarily because the small red algae have lower areal biomass concentrations than the large kelps. (Note that red algae can have high biomass concentrations in tank or pond culture). Assuming a seaweed nitrogen content of 5% (30% protein), a *Porphyra* farm in western Long Island Sound would remove 20 kg of nitrogen per hectare per month. The input of DIN to the western Sound estimated during 1973 was 170 tons per day (Bowman 1977) or 5100 tons per month. Red algal farms covering the entire area of western Long Island Sound from the Throgs Neck Bridge to Eaton's Neck (55,600 hectares), could assimilate only 1100 tons of nitrogen per month, or 20% of the total DIN input to the western Sound during summer.

Nutrient measurements within natural seaweed populations support the conclusion of the nitrogen-removal calculations that huge areas of highly productive kelp farms would be necessary to have a significant impact on DIN concentration in western Long Island Sound. In contrast to microalgae, seaweeds have never been demonstrated to deplete nutrients in an open water situation, including dense forests of *Macrocystis pyrifera* several kilometers long (Jackson 1977). Production on many of the kelp farms in China and Japan is enhanced by the application of chemical fertilizers. The need for fertilizing is based on naturally low DIN concentrations at these sites, rather than on depletion by the seaweeds. Fertilizer is applied in porous pots or as a surface spray from boats, and uptake efficiency by the seaweeds is estimated to be low, 15% or less in large Chinese farms (Tseng 1981), due to low residence time of the nutrients.

Reduction of microalgal production by light-limitation

Seaweeds can compete successfully against phytoplankton for light. Extensive seaweed farms with high biomass densities located near the surface would effectively shade the water column and reduce microalgal production. The surface canopy in natural forests of *Macrocystis pyrifera* reduces irradiance by 80-90%. A *Laminaria saccharina* farm with a high density of plants in the upper 4-5 m of the water column should have an even greater effect on irradiance. Phytoplankton production was reduced by 95% below natural kelp canopies in South Africa (Borchers and Field 1981). In order for shading by seaweed farms to effectively reduce microalgal production in western Long Island Sound, however, a large proportion of the area would have to be covered.

Economic profit

If commercially valuable seaweeds were produced, seaweed farms in western Long Island Sound might be economically self-supporting or even profitable. The annual world seaweed crop, mostly used for food and phycocolloid production, is valued at billions of dollars. Seaweed grown in western Long Island Sound would not be valuable as food if the water contains high levels of coliforms, heavy metals, pesticides, or other contaminants. One criterion for siting *Porphyra* farms in Puget Sound is the absence of sewer outfalls within 1 mile and low coliform counts (Mumford 1987). Seaweeds are generally effective accumulators of heavy metals (IAEA 1985), although they would not necessarily reduce environmental concentrations. If contaminants are a problem, the seaweed biomass would be still be valuable for phycocolloid extraction.

Enhancement of local sport fishing

Dense accumulations of macroalgae and fouling organisms on a seaweed farm might attract and support substantial populations of grazing and predatory fishes. While it seems doubtful that commercial fishing would be enhanced, seaweed farms might enhance sport fishing in western Long Island Sound in the same way as artificial reefs.

PROBLEMS OF FARMING SEAWEED IN WESTERN LONG ISLAND SOUND

Environmental conditions

Long Island Sound has an enormous temperature range, a large salinity range, and high turbidity. Combined with a dearth of hard substrata along the shore of Long Island, these conditions make the Sound a generally poor site for seaweeds. The local flora is low in both diversity and biomass. In a farm situation, the substratum problem is solved by providing ropes or nets, and the turbidity (low irradiance) problem is solved by fixing or floating the substratum at a shallow depth. Low salinity can be dealt with by culturing euryhaline species.

Seasonal temperature variation probably presents the biggest problem in farming western Long Island Sound on a yearround basis. Surface temperature ranges from $-1^{\circ}C$ during January-February to $23^{\circ}C$ or higher during August-September of a warm summer. While a number of macroalgal species can survive this range, none can maintain significant growth rates at both ends of the range. This problem led the New York Marine Biomass Program to adopt a multispecies approach, cultivating *Laminaria saccharina* as a winter crop and *Gracilaria tikvahiae* as a summer crop (Brinkhuis et al. 1987). Ideally, a seaweed crop would be planted once and the same plants harvested repeatedly, as is possible with *Macrocystis pyrifera*. The multispecies approach increases the length of the low-biomass period which follows planting (during which areal production and, therefore, nutrient assimilation are low) and increases labor costs involved in seeding or planting. It also increases development and materials costs to the extent that the different species require different treatment or technologies.

Large-scale production of a warm-water seaweed during summer might effectively reduce microalgal production. Residence time of surface water in western Long Island Sound is relatively short (one to several weeks; R. Wilson, personal communication). If summer microalgal production is the main cause of hypoxia, winter farming might be unnecessary. Planting time could coincide with temperature reaching the minimum for growth of the selected species. Because temperature remains low throughout the spring, not reaching 10°C until May, a summer crop probably would be planted in late spring and would have little effect on microalgal production until mid-summer when sufficient biomass was accumulated. Summer farming would have no impact on the spring bloom in late February.

The ideal species does not exist

The ideal seaweed species for a farm in western Long Island Sound would have the following characteristics. It would occur locally, which would circumvent the ecological and political problems involved in introducing an alien species, and would increase the probability of survival under local conditions. It would be suitable for growth on artificial substrata. It would have both rapid growth and the ability to grow at high biomass densities, in order to achieve high rates of areal production and nutrient assimilation. It would have low water content and high nitrogen content to maximize nutrient assimilation. It would be long-lived and attain large size, which would reduce planting and harvesting costs. It would have commercial value, which would offset costs. It would have a history of cultivation and domestication, which would reduce research and development costs and increase the probability of success.

The common kelp, *Laminaria saccharina*, exhibits a number of the characteristics desirable in a crop species for nutrient removal (Table 1). It is relatively abundant in central and eastern Long Island Sound, and may occur on the northern shore of the western

Sound. It is a large, perennial plant which occurs naturally in dense, highly productive stands. It has a dry content of 20% and can accumulate 3-5% nitrogen. It contains alginate, an important commercial product in the U.S. (30% of world production). Farming and domestication techniques have been developed for a similar species in China and Japan.

The fatal flaw of *Laminaria saccharina* is its temperature range. Kelps are cold-temperate species; few species survive and none grow well above 18°C. Long Island Sound is the southern geographic limit for *L. saccharina*, which acts essentially as a winter annual. Less than 1% of the kelp population in the Sound survives a warm summer, such as 1991. *L. japonica* shows a similar temperature response, and the Chinese overcome the problem by growing the microscopic and juvenile stages during the summer in greenhouses with chilled seawater. Plants are not transferred to the farms until sea temperature drops below 18°C, and are harvested in early summer. The NYMBP attempted to use the Chinese approach to farm *L. saccharina* in central Long Island Sound. Juvenile plants, initiated in May and scheduled for outplanting in October, were not actually planted until February. Although reasonable growth rates were obtained, the short growing season coupled with relatively high losses due to strong currents, storms, and poor design resulted in a low yield. The NYMBP kelp farm lasted only one year, which was not a sufficient test of the system. Even if high yields were attained, however, *L. saccharina* could be grown in western Long Island Sound only during October through June.

The west coast Marine Biomass Project identified giant kelp, *Macrocystis pyrifera*, as the most likely candidate species for biomass production. This species is not native to the Atlantic coast. Its main advantage over *Laminaria saccharina* is that it produces a surface canopy which can be harvested repeatedly without replanting. This advantage would be of little use in Long Island Sound, where the species would probably act as an annual due to its poor tolerance of temperatures above 20°C. Giant kelp may exhibit poor survival and growth at temperatures below 5°C and at low salinities. Finally, adult plants would lose large amounts of biomass from the surface canopy if ice formed during winter.

The brown alga, *Sargassum filipendula*, is a benthic relative of the well-known pelagic *Sargassum* species. It occurs as a summer annual in Long Island Sound and grows well at 18-30°C. Prelminary studies as part of the Marine Biomass Program indicated growth rates comparable to those of the kelps (Hanisak 1987). It loses large amounts of biomass, however, when it becomes reproductively mature in late summer. Another possible drawback to *Sargassum* as a nitrogen assimilator is that growth of this species may be limited more by phosphorus than by nitrogen.

Another brown alga, *Ascophyllum nodosum*, is a perennial, intertidal species which occurs in Long Island Sound. Although this species apparently gave good yields in land-based spray culture (Moeller et al. 1984), it is not naturally a highly productive plant. Furthermore, it may require periodic exposure to air, which would preclude production in deep areas of the Sound. Both *Sargassum* and *Ascophyllum* contain the commercially valuable phycocolloid, alginate. Because neither of these species has been grown commercially, both would require a lengthy research and development period.

Several species of *Porphyra* occur in Long Island Sound. These are morphologically and physiologically similar to the species grown as *nori* in Japan and China, and would be summer crops. The technology has been developed to seed nets with *Porphyra* and store them frozen for long periods prior to planting. Seeded nets could probably be purchased from Japan. It is unlikely that *Porphyra* produced in western Long Island Sound would be acceptable as food.

The red alga, *Gracilaria tikvahiae*, was examined as a potential biomass species in Long Island Sound (Brinkhuis et al. 1987). It is a native species with optimal growth at summer temperatures (20-25°C). The NYMBP did not succeed in growing *Gracilaria* on its floating farm, primarily because the fragile morphology of this species makes it susceptible to breakage by waves and currents. It is commercially valuable for agar extraction.

Irish moss, *Chondrus crispus*, is a yearround native to Long Island Sound and an ecologically important intertidal species. While it can survive under the full temperature range of the Sound, maximum growth of this species occurs at 15°C. It is harvested commercially for carrageenan and has been grown experimentally in tanks, but not on ocean farms. As noted above, the small red seaweeds have a lower areal biomass and production rates than the more robust kelps, and would probably be less effective in nutrient removal.

The green alga, *Codium fragile*, was introduced unintentionally to Long Island Sound, and has been very successful as a weed. It was examined, but not field-tested, as a potential biomass crop by the NYMBP. *Codium* can achieve fairly high growth rates with maximal growth at 24°C and 24-30°/oo salinity. It fragments at low temperatures. Its two biggest drawbacks are high water content (95%) and lack of commercial value. It also has cyanobacteria, and often high rates of nitrogen-fixation, associated with it.

Another genus of green algae, *Ulva* spp., is harvested for food in Japan, although not cultivated on a commercial scale. Related species have been tested both as a biomass crop and for nitrogen removal in waste treatment. This seaweed is a summer annual in Long Island Sound, and grows very rapidly at high temperatures. It is also euryhaline. Its major drawback is its very fragile thallus, which would be easily broken or lost from a floating farm.

None of the above species exhibits the ideal combination of rapid yearround or at least summer growth, high productivity and nitrogen assimilation, adaptability for farm cultivation, commercial value, and existing culture techniques.

Seaweed farms as potential causes of hypoxia

Phytoplankton production causes hypoxia in western Long Island Sound only when the produced organic matter sinks below the thermocline under stratified conditions and decomposes. Seaweeds growing on a near-surface farm would also contribute organic matter to deep water and the benthos. Seaweed biomass that is lost as large pieces (whole plants and large fragments) would be transported to the benthos even more rapidly than sinking phytoplankton cells. Loss from Chinese kelp farms was estimated to be 60% of produced biomass (Brinkhuis 1987). If this estimate is accurate, over 20 dry tons of seaweed biomass is lost per hectare during the 9 month growing season, most of which must reach the benthos. This amount greatly exceeds organic input to the benthos from phytoplankton production. Seaweed tissue generally has a low proportion of refractory materials and decomposes rapidly. Seaweed farms, therefore, have the potential to cause much worse hypoxia than already exists in western Long Island Sound. Large subsurface farms would also reduce mixing effects of wind, further aggravating oxygen depletion.

Fouling organisms

Long Island Sound has large populations of benthic invertebrates with planktonic larvae, such as mussels and barnacles. The larvae recruit seasonally and settle on just about any hard substratum, including nets, ropes, buoys, and seaweeds. The NYMBP experimental farm sank from 2-4 m to 7-12 m depth during August 1984, due to the growth of mussels which recruited during spring. *Laminaria saccharina* remaining on the farm at that time were completely overgrown by mussels. Potential problems with and solutions to fouling in western Long Island Sound may be well known from experience with ships, docks, etc.

Navigational hazards, competitive uses, and vandalism

Extensive seaweed farms located in western Long Island Sound would be a navigational hazard for commercial ships and recreational boats. The few seaweed farms that have been attempted in the U.S. have caused at least one documented and probably several undocumented accidents. Extensive seaweed farms would limit use of western Long Island Sound by commercial fishermen and recreational boaters. The attitude of those groups toward aquaculture projects which compete for use of coastal waters is generally negative. Vandalism would be a problem.

Costs

The costs of designing, testing, constructing, and operating extensive seaweed farms in western Long Island Sound would be considerable. Because none of the species which are now farmed commercially are suitable for yearround production in western Long Island Sound, development time would probably be on the order of a decade. Although construction costs are relatively low for Chinese and Japanese-style farms, the cost of mooring large farms against the strong tidal currents in western Long Island Sound might be prohibitive. Chinese kelp farms and Philippine *Eucheuma* farms are planted, tended, and harvested by hand. This approach would be extremely expensive in New York. Japanese *nori* farming is more mechanized, but still requires a fair amount of labor for seeding nets.

The success of seaweed farming in China is largely attributable to a low technology approach, long development period (about 30 years), and cheap labor. Cultivation methods and seaweed strains were improved gradually, largely by trial and error. Seaweed farming in the Philippines and Indonesia have similar histories. The Japanese, who have the longest history of seaweed cultivation (200 years), have recently taken a more high technology approach. They are financially successful only because their product is in high demand and demands a high price. Seaweed farming in New York would be forced to take a high technology approach due to high labor costs, without the benefit of a high-demand product.

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Table 1. Characteristics of potential crop species.

Genus	**Characteristics**	**Cultivation**
Ascophyllum	large brown robust local, perennial slow growth	none wild populations harvested for alginate
Chondrus	small red moderately robust local, perennial max growth at 15°C	experimental in ponds wild populations harvested for carrageenan
Codium	small green moderately robust introduced to LIS summer growth high water content	none no commercial value
Gracilaria	small red delicate local species summer growth	experimental in tanks and on NYMBP farm for agar, biomass, and waste treatment
Laminaria	large brown local species winter growth high summer mortality	commercial on rafts in China and Japan for food and alginate
Macrocystis	giant brown robust, surface canopy no local species	experimental for biomass on ocean farms in California wild populations harvested for alginate
Porphyra	small red delicate local species summer growth	commercial on rafts in China and Japan for food
Sargassum	large brown moderately robust local species summer growth	experimental for biomass in ponds
Ulva	small green delicate local species summer growth	experimental in tanks for waste removal

TIDE GATES AS MEANS OF ALLEVIATING HYPOXIA IN WESTERN LONG ISLAND SOUND

AND

REDUCING WATER POLLUTION IN NEW YORK/NEW JERSEY HARBOR WATERS

BY

TADEUSZ J. MARCHAJ
PRELOAD INC.

839 STEWART AVENUE
GARDEN CITY, NEW YORK. 11530

November 21, 1991

INTRODUCTION

Long Island Sound - "American Mediterranean" bounded by Long Island on the south and Connecticut and New York on the north extends about 100 miles from west (at Throgs Neck) to east (at New London, Conn.) with an area of about 1300 sq.miles and an average depth 70 feet (see dwg.1).

Five million people live within 15 miles of the Sound and 18 million people live within 30 miles of the coast.

The Long Island Sound is one of the most important commercial and recreational water bodies in the states of New York and Connecticut The Sound has 248 miles of beaches 95 miles publicly owned.
In 1988 six million people visited stateowned beaches. There are 200,000 boats registered, 20,000 boat slips and 750,000 recreational fishermen. Sport fisheries were worth $70 - 130 million to economy in 1987 and commercial fisheries were worth $ 36 - 40 million.

Increase in population and in commercial and industrial concentration around the Sound have increased waste disposal to such a degree that water quality in the Sound has reached unacceptable levels. In 1987 the Sound experienced a major disaster, when millions of fish were killed by hypoxia.

Reasons cited for these new conditions in the Sound are the 44 (forty four) sewage - treatment plants, which discharge directly into the Sound at the rate of about 2 billion gallons of waste per day. Most of these sewage treatment plants are located in the western part of the Sound or at the East River and New York/New Jersey harbor waters. Most of the sewage-based nitrogen and phosphorus are linked to low oxygen or hypoxia in the Sound (see dwg.2)

Each year about 120 billion gallons of surface runoff from rainfall is added to the disposed sewage into the waterways of the N.Y./N.J. harbor. In spite of the fact that this rainwater runoff presents little health hazard it does wash hundreds of thousand - if not millions of pieces of garbage into the water which drift to the shores and create unhealthy conditions for people and animals.

About an equal amount of nitrogen and phosphorus is entering the waters of the Sound through the river systems that drain runoff from inland farms and towns from about 16500 sq.miles of the states north of the Long Island Sound.

Fortunately for the New York/New Jersey harbor area movement of the waters due to tidal action has some cleansing effect as water brought to harbor by tide waves dilute the disposed sewage. The harbor area is accessible to tides movement from two directions: from the south through the Narrows and from the east through Sound and Hell Gate. On the average the net tides flow is in the southern direction and a small portion of the clean water from the Sound is diluting highly polluted water in harbor. On the other hand, when tides are entering the Sound from the N.Y./N.J. harbor highly polluted water enters mainly in the top layer and has very little chance to flow back when the tide movement changes direction.

Exchange of the waters due to tidal movement between the N.Y/N.J. harbor and the Sound, and subsequent stratification of polluted waters in western Sound is the primary reason for the development of hypoxia.

"Hypoxia - the technical term for low dissolved oxygen concentration in water- occurs in the L.I.S. waters in late summer in the bottom layer of water below a density gradient set up by differences in temperature and salinity between the surface and bottom layers of water. The respiration of oxygen-breathing organisms in the lower water column and in the sediments uses up the available oxygen,reducing its concentration in the water. If the water remains stratified for extended period and the amount of organic carbon - such as decaying organic matter - available to consume oxygen is high enough,oxygen may fall to hypoxic or even anoxic level....The LISS has identified nitrogen as the nutrient most directly linked to the causes of hypoxia in the Sound.Discharge from sewage treatment plant and non point runoff are primary sources of the increased nitrogen load. The enriched level of nitrogen allow algal growth in excess of natural productivity levels. The algae die, sink to bottom of the Sound, and decay. During decay, oxygen is consumed. Because there is more decaying algae than was naturally produced when nitrogen inputs were smaller, a correspondingly larger amount of oxygen is used up in the decay process. A recent summary of dissolved oxygen measurements indicates that minimum dissolved oxygen levels have fallen over the last four decades,especially in the extreme western Sound" (Ref.1).

Without some corrective action the conditions described above will eventually change the Sound in " the Dead Sea " of North America.

RESTRICTED FLOW AND USE OF TIDE BARRIERS.

The purpose of this paper is to propose a technological solution which will increase the cleansing action of the N.Y./N.J. harbor by the tides without any detrimental effects on the Sound. In fact the proposed solution will improve water conditions in the Sound.

To accomplish these goals it is proposed that semi - barriers have to be erected at a properly selected point between Lawrence Point and Throgs Neck on the East River. The barriers will be effective (i.e. closed) only when tidal currents move in a eastward direction, and be temporarily removed (i.e. will open) when tidal currents change to a westward direction.

To avoid the total separation of the waters of the Sound from those of the N.Y./N.J. harbor the barrier will not close entirely a selected passage whenever tidal currents flow eastward but the barrier will be totally open when tidal current will be in westward direction (see dwg.3)

The barrier arrangement will be such as to always allow a passage for commercial or recreational traffic, which when heading westward and passing through opening at the time when barrier are closed has to negotiate the eastward currents.The traffic heading eastward at the same time will move through opening with the currents.

The ratio of length of opening to total length of passage must be established by considering the current velocity through the barrier opening in relation to manageable velocity of the vessels when negotiating the barrier line.

Design and erection of modular barriers is not a major engineering problem. Various type of barriers can be considered (see dwg.4) but it is very important at the design stage to introduce structural features which will enhance the mixing of water when passing the line of the barrier. Such features could eliminate or significantly decrease possibility of stratification formation in the waters which will pass the barrier.

Free flow of the westbound will deliver about 1.5 billion cub.ft of water a day (about 10 billion gallons) from the Sound into the N.Y./N.J. harbor. Actual volume of this flow will vary from day to day depending on weather or seasonal conditions, but the average amount will be more than 10 x (ten times) greater than the sewage disposed in N.Y./N.J. waters.

The reduction of the tide flow in an eastward direction will depend greatly on acceptable current velocity in opening in the barrier. The simplicity of modular construction, and therefore low cost of the barrier will allow a "cascade" arrangement of the barriers within the East River between Lawrence Point and Throgs Neck. The shape of the East River between these two points allows the consideration such a "cascade" solution. (see dwg. 5)

To reduce floating garbage in the waters of the Sound and the East River specially designed devices may be placed within the barriers to intercept floating matter.

The flow - restricting barriers can be set up to operate only when there is a need to bring the oxygen level to normal and can be left in open position in winter time when heavy ice formation is expected.

The anticipated cost of one barrier line (based on the cost of flood protective gates across the Thames River in England) should not be greater then $500 million.

Regardless of the barrier type (flap gates, vertical gates, floating gates) the power requirements to initiate movement or lock the gates in open or closed position, will be minimal.

RECOMMENDED STUDY.

A. Geological survey of the bottom of the East River for proper location of the barrier.

B. Modeling and study of the flow around the barrier with emphasis on the best mixing effect of two layer flow.

C. Modeling and study of the best location of the barrier from the hydrodynamics point of view for single or double line of barriers.

D. Modeling and complex study of the western Sound, the East River, New York harbor and Hudson River after the installation of the restricting flow barriers in the East River (Physical, chemical, environmental and ecological changes and their acceptance).

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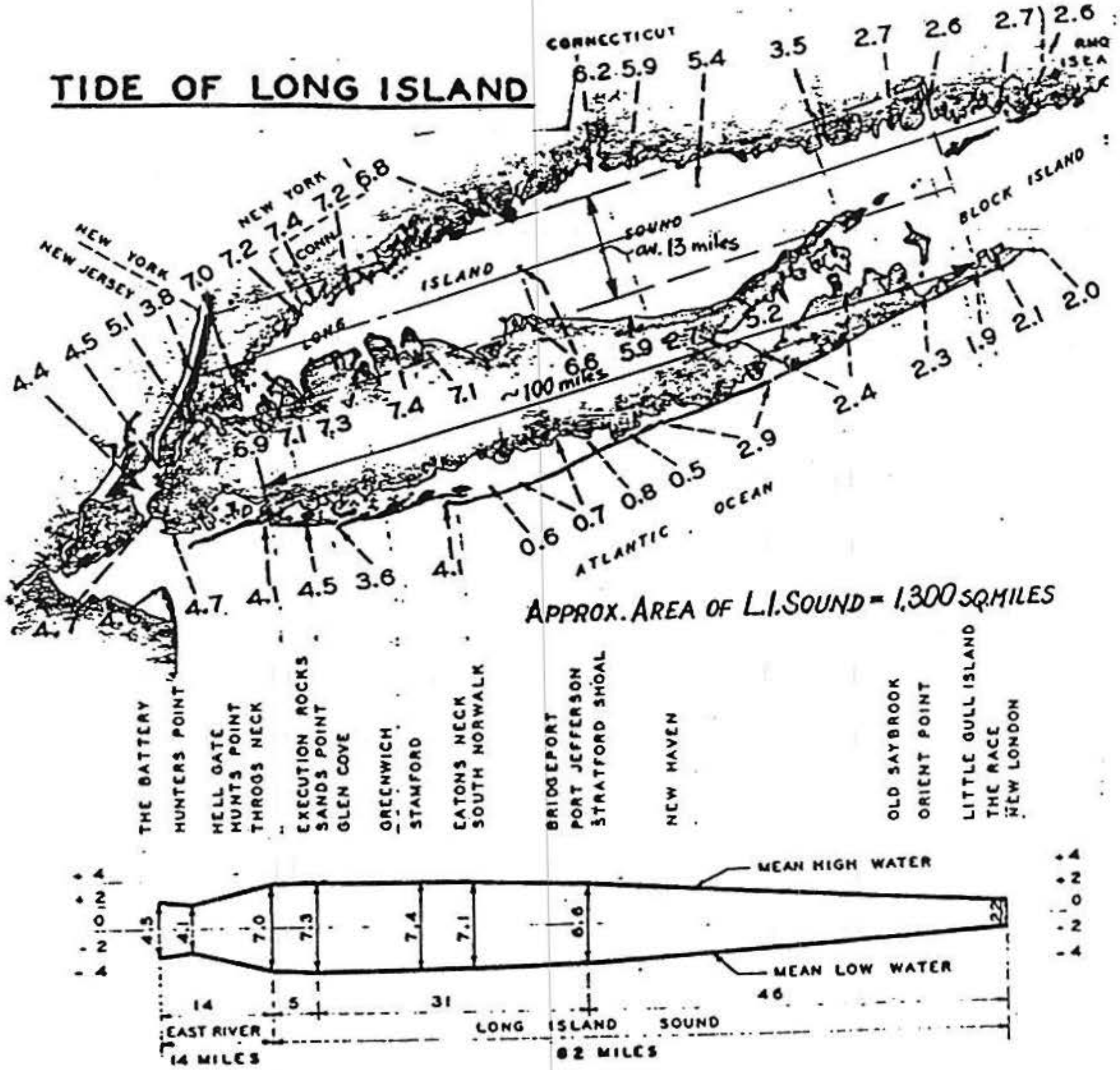
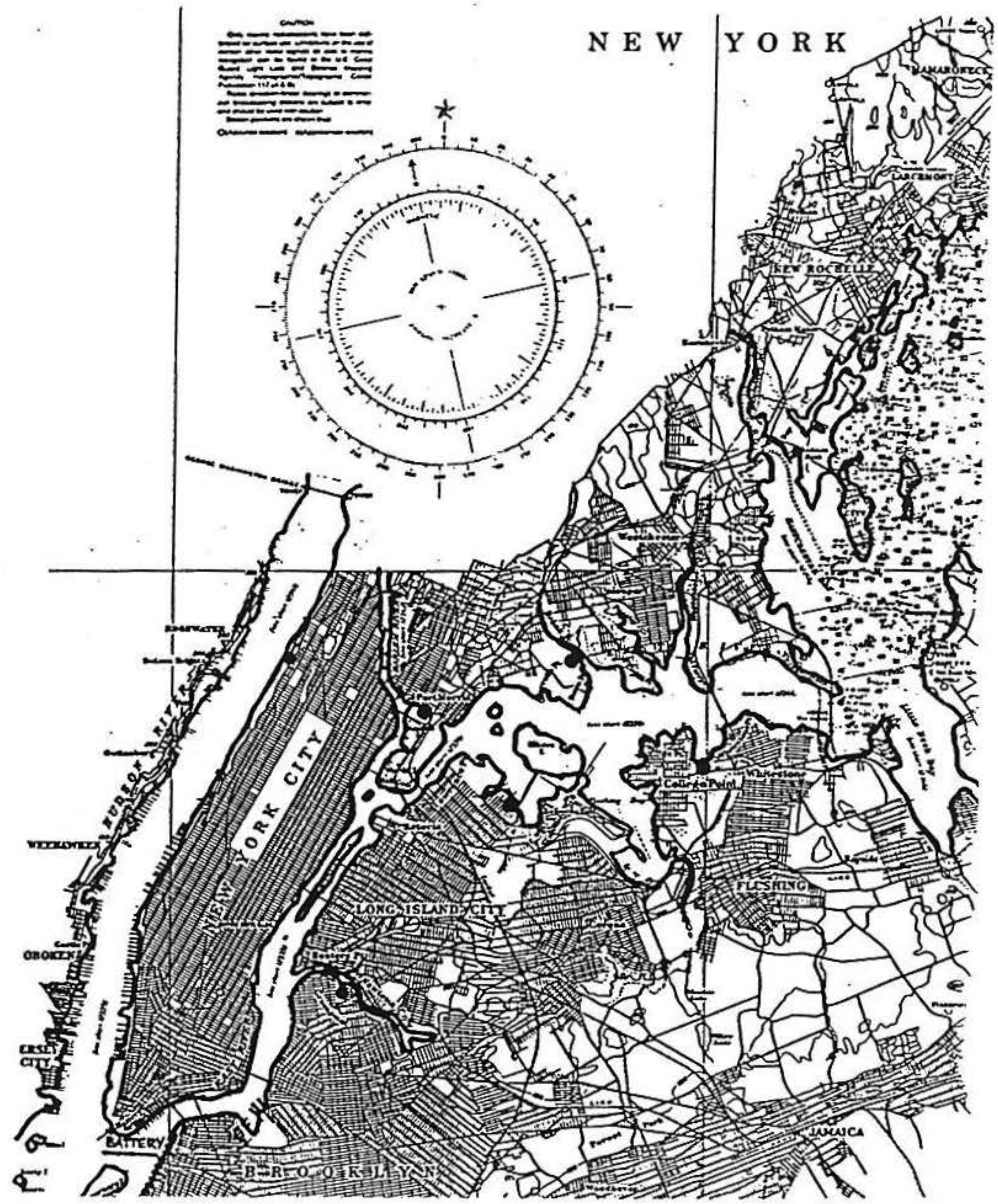


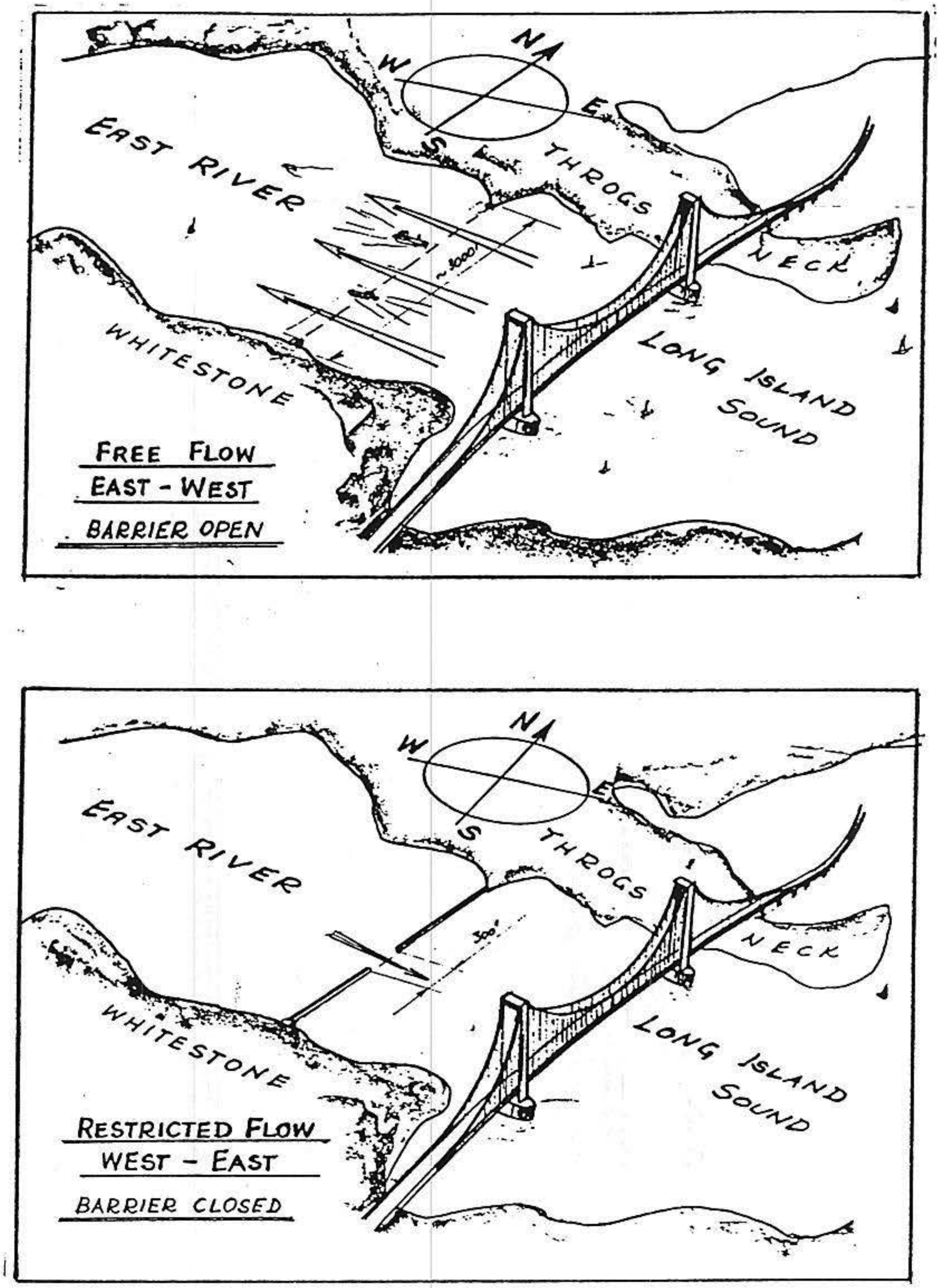
TIDE OF LONG ISLAND

DWG. 1



DWG 2.

- MAJOR SEWAGE TREATMENT PLANT


N
W
E
S
EAST RIVER
THROGS
NECK
WHITESTONE
LONG ISLAND SOUND
3000'
FREE FLOW
EAST - WEST
BARRIER OPEN
N
W
E
S
EAST RIVER
THROGS
NECK
WHITESTONE
LONG ISLAND SOUND
300'
RESTRICTED FLOW
WEST - EAST
BARRIER CLOSED

DWG. 3.