William J. Cahill, Jr.
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July 8, 1976

Director of Nuclear Reactor Regulation
Attn: Mr. George W. Knighton, Chief
Environmental Projects Branch No. 1
Division of Reactor Licensing
United States Nuclear Regulatory Commission
Washington, D. C. 20555

Re: Docket No. 50-247

Dear Mr. Knighton:

In response to your letter dated March 26, 1976, received on March 31, 1976 and the accompanying list of questions to which you requested answers, we have attached hereto responses to questions A: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 15, 17, 18, 23b and c, 23d, 25e, 25f, and B: 1 and 2.

The answers to the balance of the questions will be submitted when available, and we intend to complete these answers by the requested date of September 30, 1976.

Sincerely,

William J. Cahill, Jr.

jbw/klg

cc: Stephen Lewis, Esq.
Michael Curley, Esq.
Sarah Chasis, Esq.
Paul Shemin, Esq.

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Question A.1:

Define the concept of a "total standing crop estimate" as used in Table II-1, Page II-9, for separate life-stages. Explain whether this quantity is the same as, or similar to, either an average standing crop (over some specified period) or a peak standing crop.

Response:

"Total standing crop estimate" as used in Tables II-1 and II-2 represents a standing crop estimated over a several day period representing a portion of a single sample interval; i.e., two weeks during 1973 and one week during 1974. A single estimate of "total standing crop" was made for each life stage during each sample interval by summing all regional standing crop estimates made during that interval. This procedure, therefore, is similar to an average standing crop over a specified period of time.

Question A.2:

On the second line of Page III-9, clarify whether the term "relative" refers to the water or to the bottom.

Response:

The term "relative" is in reference to the water. It is used to relate the movement of the gear through the water.

Question A.3:

On pages III-14, III-15, III-19, III-23, and III-30, reference is made to the random selection of individuals from samples. Explain the method by which such random selections were made, and explain whether the success of the method has been tested.

Response:

Methods of subsampling from fisheries collections varied among tasks. The procedures followed for each task identified in question A.3 are outlined as follows:

Page III-14 - This section describes efforts used to subsample striped bass and white perch juveniles collected by beach seines for length measurement in the field. Individuals collected in each seine haul were sorted as to species and juveniles identified on the basis of length. Juveniles were held in tubs to which MS 222 had been added prior to subsampling and marking. Subsampling was carried out by netting individuals from the tubs until a total of 25 had been measured. If the sample contained fewer than 25 individuals all were used. Because of the anesthetic, net avoidance was not a factor in selection of the subsample. Specimens were subsequently marked and released.

Page III-15 - This section describes procedures used in the laboratory to subsample juveniles of species other than white perch and striped bass from samples collected by beach seines and preserved before their return to the laboratory. Fish were sorted into categories by species and juveniles identified by length. If the category contained 20 or fewer individuals, all were measured. If the category contained more than 20 individuals, the specimens were thoroughly mixed in a pile and a "handful" estimated to contain 20 individuals was taken. If the actual number taken was between 15 and 25, then all those specimens comprised the sample, if the number was greater than 25, the first 25 counted were used; if fewer than 15 were taken, another grab was made to include enough individuals to bring the total to between 15 and 25.

Page III-19 - Bottom trawl collections made during 1973 were either processed in the field or returned to the laboratory. In the field individuals were identified to species and sorted into the size categories indicated. Individuals were arbitrarily taken one at a time from those available on the deck of the boat until 20 had been measured. If the sample contained fewer than 20, then all were measured. Samples returned to the laboratory were processed as described above after sorting into appropriate species and size categories.

Page III-23 - This section describes subsampling procedures carried out in the laboratory on bottom trawl collections made during 1974. After separation into appropriate categories subsampling occurred as described above (III-15) for beach seine collections.

Page III-30 - This section describes subsampling procedures used in the laboratory on standard-station collections made during 1973. Individuals were first sorted into categories by species and size. If the category contained 20 or fewer individuals all were measured. If the category contained more than 20 individuals the specimens were thoroughly mixed in a pile and a "handful" estimated to contain about 20 individuals was taken. If the number was greater than 20, the first 20 individuals counted comprised the sample. If the number was less than 20 another "handful" was taken and enough individuals counted to bring the subsample size to 20.

None of the above subsampling procedures were tested to check the similarity of the subsample composition to that of the original sample.

Question A.4:

On Page III-19, clarify whether the velocity of approximately 1.3 m/s is relative to the water or to the bottom.

Response:

The velocity of approximately 1.3 m/s is relative to the water.

Question A.5:

Provide the full reference and a copy of Simpson et al., 1973, which is cited on P. IV-12.

Response:

The complete reference is as follows:

Simpson, H. J., R. Bopp, and D. Thurber. 1973.
Salt movement patterns in the Hudson, Paper 9. In: Hudson River Ecology. Third Symposium on Hudson River Ecology, March 22-23, 1973. The Hudson River Environmental Society.

A copy of the paper is attached.

Question A.6:

For the seines described in the column headed "Length (ft)" in Table V-2 (page V-17), please provide information about their depths and mesh sizes.

Response:

The following table provides information requested on depth and mesh size of beach seines described originally in Table V-2:

STUDY	YEAR	SEINE LENGTH	SEINE DEPTH	SEINE MESH
N.Y.U.	1965-1969	50 ft total length; 4 ft central bag	wings, 4 ft bag, 6 ft	3/8 inch square throughout
Raytheon	1969	75 ft total; no bag	8 ft	1/4 inch square
Raytheon	1970	100 ft total length; 20 ft central bag	wings, 10 ft bag, 20 ft	wings 3/8 inch sq. bag 3/16 inch sq.
T.I.	1972	75 ft total length; no bag	8 ft	1/4 inch square
		100 ft total length; 20 ft central bag	wings, 10 ft bag, 15 ft	wings 3/8 inch sq. bag 1/4 inch sq.
T.I.	1973-1974	100 ft total length; 20 ft central bag	wings, 10 ft bag, 15 ft	wings 3/8 inch sq. bag 3/16 inch sq.

Question A.7:

Confirm whether the probability level "p = 0.32" in the text on P. V-37 should in fact be "p = 0.032". Supply "r" and "p" values for striped bass for the months of March, May, June, and July, as has been done for white perch on P. V-37.

Response:

a. The probability level "p = 0.32" reported in the text on P. V-37 should indeed have been reported as "p = 0.032."

b. The table below presents "r" and "p" values for the relationship between striped bass juvenile abundance and freshwater discharge for the months of March, May, June, and July as requested. Probabilities reported are for a two-tailed test.

Month	r	p
March	+0.107	0.784
April	+0.711	0.032
May	+0.196	0.614
June	+0.069	0.861
July	+0.028	0.944

Question A.8:

Why have the studies of King and Tatham on the swimming-speed capability for striped bass, both of which were financed by Consolidated Edison, not been included in Tables VI-2 and VI-3 (pp. VI-7 and VI-8)?

Response:

Information presented in Tables VI-2 and VI-3 includes the results of the King and Tatham studies although direct reference to these and other studies has been omitted from the tables. These papers are cited in the Literature Source Section at the end of Section VI (pp. VI-90 and VI-91). Citations within Tables VI-2 and VI-3 are of papers describing the test apparatus used in the King and Tatham studies, as well as in other studies summarized in these tables.

Question A.9:

Please supply a clarification of the fourth assumption (beginning with the word "strata") on page VI-13.

Response:

The fourth assumption on page VI-13 should read as follows: Strata within a geographical river region are sampled independently of each other so that the variance associated with each geographical region standing crop estimate is the sum of the strata variance. The same assumption of independence among geographic regions is made; the variance of the entire river standing crop is the sum of the geographical region variances.

Question A.10:

Provide a clarification of the top histograms in Figure VI-14 (p. VI-70) and VI-15 (p. VI-72). Were fish marked in one area but released in another area?

Response:

All fish were released within the region in which they were captured. However, some fish captured within certain regions were clipped with the wrong fin-clip type for that region. The exact numbers of fish released with incorrect fin-clip types are presented in Tables D-137 and D-138 (pp. D-137 and D-138) in Volume II of the First Annual Report for the Multiplant Impact Study of the Hudson River Estuary.

Question A.11:

Table VI-6 on Page VI-15 is inconsistent with Table J-1 of the draft of Texas Instruments, Inc., September 1974, "Fisheries Survey of the Hudson River, March-December 1973, Volume IV, Prepared for Consolidated Edison Company of New York, Inc." (hereafter referred to as "draft Volume IV."). Other inconsistencies or discrepancies between the Multiplant Report and Draft Volume IV are apparent. Please supply a final version of Volume IV, as referenced on Page IX-9, or an errata list for the draft Volume IV, or both.

Response:

Differences between draft Volume IV and the First Annual Multiplant are in the process of being rectified. The population estimates in particular were preliminary when incorporated into draft Volume IV and will be corrected in the final Volume IV to correspond with the final estimates in the Multiplant Report.

Question A.15:

On p. VI-88 it is stated that: "Through the combination of sound-field-sampling programs, intake-design modification, and manipulation of the plant pumping rates and schedules, power-plant impact of the striped bass, white perch, and Atlantic tomcod populations in the Hudson River estuary can be minimized." Provide details of such a plan including a benefit-cost analysis.

Response:

Con Edison is currently utilizing and studying several measures to mitigate impact at Indian Point to striped bass, white perch, and Atlantic tomcod. These measures are detailed in "A Plan of Action of Operating Procedures and Design Modifications of The Once-Through Cooling System for Indian Point Unit No. 3," submitted to the NRC on May 5, 1976.

A benefit-cost analysis will appear in an Environmental Report to accompany Con Edison's application to delete from the license the requirement to terminate operation of the once-through cooling system, which Con Edison expects to file, if justified by the results of the ecological study program, early in 1977.

Question A.17:

Confirm with respect to the first equation on p. VII-12, whether an exponent "j" has been omitted from the left-hand term, and whether the quantity "q subscript p" should be a multiplier of, rather than a subscript to, the final "R" term in the denominator of the right-hand side of this equation.

Response:

The equation referred to on p. VII-12 should appear as

$$\sum_{j=0} R(1-q_p)^j = \frac{1}{1-R+Rq_p}$$

As suggested in the question "j" should appear as an exponent on the left side of the equation and "q_p" should be a multiplier of, rather than a subscript to, the final R on the right side.

Question A.18:

In application of the equation at the top of the page VII-14 to the estimation of entrainment impact, are striped bass life stages (e.g., eggs, yolk-sac larvae, etc.) treated separately, or are they combined into a single quantity called striped bass ichthyoplankton (except for the obvious separation of eggs for purposes of adjusting the standing crop estimates on page VII-7)?

Response:

In the application of the equation

$$q_{ie} = \frac{E_{ki}}{N_i^*}$$

to produce an estimate of the proportion of a year class of striped bass (or white perch) cropped by entrainment by a single power plant during one time interval (q_{ie}) all ichthyoplankton life stages are combined into a single quantity. E_{ki} represents the total number of individuals of all life stages killed by

entrainment, and N_i^* represents the total standing crop of all ichthyoplankton life stages adjusted for unspawned eggs.

Question A23b and c:

With respect to the analysis of stock-recruitment relationships beginning on p. VIII-2:

b. Provide an analysis and discussion of results of the white perch stock-recruitment relationships with recruitment measured 3, 4, and 5 years after stock.

c. Provide an analysis and discussion of results of the American shad stock-recruitment relationships with recruitment measured 4, 5 and 6 years after stock.

Response:

Data from several sources on the striped bass, white perch and American shad populations were used to investigate the role of density dependence in stock-recruitment relationships. A statistically significant linear regression fit was obtained for striped bass but not for the other two species. Since no similar statistical relationship was demonstrable for either American shad or white perch, further analyses for these species were not pursued. We have enclosed the raw data upon which the graphical analyses for these two species were based.

Table 1 is the raw data presented in the First Annual Report for the Multiplant Impact Study of the Hudson River estuary (i.e. Table V-1, Page V-6). This Table includes corrections which shall appear in an errata for this report. The numbers appearing in Table 2 and 3 were calculated from the data in Table 1. You may plot these data as the striped bass data wereplotted in Page VIII-4 of this report. You would appropriately test the fit of the curve by a non-linear least-squares method to either Ricker (1954, 1958) or Beverton-Holt (Ricker, 1973) type models. The linear regression analysis shown in the subject report only applied to a portion of the curve and would not be appropriately applied to the total plot.

TABLE 1 Commercial Fishery Statistics for Striped Bass, White Perch, and American Shad Taken from Hudson River, 1931-1972.

DATE	REPORTED LANDINGS (LBS) STRIPED BASS	WHITE PERCH	AMERICAN SHAD	FISHING EFFORT LICENSED FISHERMEN	NO. OF GILL NETS	NO. OF GILL NETS STAKE, ANCHOR AND DRIFT TOTAL	FISHING HR ALLOWED WEEKLY	CATCH PER UNIT EFFORT STRIPED BASS	WHITE PERCH	AMERICAN SHAD
1931	5330	14436	414611	252	123	334465	108	147	400	11346
1932	4508	16325	529754	274	126	395632	108	106	382	12232
1933	13616	19235	518680	317	146	435631	108	290	409	10785
1934	10905	31225	438000	322	154	532380	108	190	543	74[illegible]
1935	18667	60552	847400	498	307	353735	108	489	1585	20989
1936	20120	46856	2467900	476	1347	471670	108	395	921	44711
1937	28854	26538	2732200	613	299	734904	108	363	334	31219
1938	24579	35421	2467000	875	599	880583	108	258	372	23755
1939	29937	24479	3270000	647	417	712014	108	389	318	37916
1940	34634	39856	3114400	648	584	663187	108	484	557	43483
1941	21336	46426	3133500	650	332	526617	132	307	668	45078
1942	---	---	3185900	549	527	374484	132	---	---	644[illegible]
1943	30889	30155	3225350	608	275	595829	150	346	337	36088
1944	60918	13848	3809400	533	489	760436	168	477	108	29818
1945	79350	17166	3477200	545	333	892100	132	674	146	29529
1946	50622	8458	2972143	936	526	1103300	132	348	58	20408
1947	48453	2249	1981792	1172	533	1325360	132	277	13	11326
1948	38830	21028	2354400	959	476	1122520	132	262	142	15890
1949	---	---	1727370	845	468	1079186	132	---	---	12126

-continued-

TABLE 1
Page 2

DATE	REPORTED LANDINGS (LBS) STRIPED BASS	WHITE PERCH	AMERICAN SHAD	FISHING EFFORT LICENSED FISHERMEN	NO. OF GILL NETS	NO. OF GILL NETS STAKE, ANCHOR AND DRIFT	TOTAL	FISHING HR ALLOWED WEEKLY	CATCH PER UNIT EFFORT STRIPED BASS	WHITE PERCH	AMERICAN SHAD
1950	---	---	1008900	522	313		970903	132	---	---	7872
1951	---	---	764100	419	197		615315	96	---	---	12929
1952	29501	2901	1077100	374	180		520127	96	591	58	21571
1953	19352	9320	938722	363	173		415855	96	485	234	235[illegible]
1954	---	---	1249286	391	198		484155	96	---	---	26879
1955	73400	9205	1510340	322	176		402785	96	1897	238	39060
1956	92824	3446	1681166	308	175		378977	96	2550	95	46209
1957	84500	6000	1497680	276	160		358408	96	2456	174	43528
1958	77100	12500	1045765	229	147		323561	96	2479	402	33667
1959	133100	8400	1171212	234	143		278247	120	3985	252	35077
1960	132900	4350	723572	211	121		270572	120	4089	134	22285
1961	70700	6300	588989	191	112		248534	120	2372	211	1974[illegible]
1962	43100	4100	527680	168	105		240340	120	1670	142	18296
1963	46700	5800	348018	142	83		191015	120	2039	253	15183
1964	29500	5700	181865	125	65		178039	120	1378	266	8512
1965	36700	3600	237521	94	58		157025	120	1952	191	12605
1966	44342	1130	116332	69	50		130271	120	2842	72	7442
1967	54642	1490	176358	71	44		126641	120	3595	98	11605
1968	60800	1700	254372	81	53		149275	120	3397	95	14200

-continued-

TABLE 1
Page 3

DATE	REPORTED LANDINGS (LBS) STRIPED BASS	WHITE PERCH	AMERICAN SHAD	FISHING EFFORT LICENSED FISHERMEN	NO.OF GILL NETS	NO.OF GILL NETS STAKE, ANCHOR AND DRIFT TOTAL	FISHING HR ALLOWED WEEKLY	CATCH PER UNIT EFFORT STRIPED BASS	WHITE PERCH	AMERICAN SHAD
1969	77155	2600	243104	76	55	132599	120	4852	164	15278
1970	45900	1400	231571	65	57	146439	120	2608	80	13178
1971	24747	200	170798	45	44	118226	120	1743	14	12039
1972	17946	---	288760	52	47	123310	120	1213	---	1951[illegible]

TABLE 2: White Perch CPUE at time t, t+3, t+4, and t+5

Catch Per Unit Effort

YEAR	CPUE (t.)	CPUE (t+3)	CPUE (t+4)	CPUE (t+5)
1931	400	543	1585	921
1932	382	1,585	921	334
1933	409	921	334	372
1934	543	334	372	318
1935	1,585	372	318	557
1936	921	318	557	668
1937	334	557	668	---
1938	372	668	---	337
1939	318	---	337	108
1940	557	337	108	146
1941	668	108	146	58
1942	---	---	58	---
1943	337	58	13	142
1944	108	13	142	---
1945	146	142	---	---
1946	58	---	---	---
1947	13	---	---	58
1948	142	---	58	234
1949	---	---	---	---
1950	---	---	---	---
1951	---	---	---	---
1952	58	238	95	174
1953	234	95	174	402
1954	---	174	402	252
1955	238	402	252	134

-continued-

TABLE 2: White Perch
Page 2

CPUE at time t, t+3, t+4, and t+5

Catch Per Unit Effort

Species: White Perch

YEAR	CPUE (t.)	CPUE (t+3)	CPUE (t+4)	CPUE (t+5)
1956	95	252	134	211
1957	174	134	211	142
1958	402	211	142	253
1959	252	142	253	266
1960	134	253	266	191
1961	211	266	191	72
1962	142	191	72	98
1963	253	72	98	95
1964	266	98	95	164
1965	191	95	164	80
1966	72	164	80	14
1967	98	80	14	
1968	95	14		
1969	164			
1970	80			
1971	14			
1972	---			
1973	---			
1974	---			
1975	---			

TABLE 3: American Shad CPUE at time t, t+4, t+5, and t+6

Catch Per Unit Effort

Species: American Shad

YEAR	CPUE (t.)	CPUE (t+4)	CPUE (t+5)	CPUE (t+6)
1931	11,346	20,989	44,711	31,219
1932	12,232	44,711	31,219	23,755
1933	10,785	31,219	23,755	37,916
1934	7,425	23,755	37,916	43,483
1935	20,989	37,916	43,483	45,078
1936	44,711	43,483	45,078	64,450
1937	31,219	45,078	64,450	36,088
1938	23,755	64,450	36,088	29,818
1939	37,916	36,088	29,818	29,529
1940	43,483	29,818	29,529	20,408
1941	45,078	29,529	20,408	11,326
1942	64,450	20,408	11,326	15,890
1943	36,088	11,326	15,890	12,126
1944	29,818	15,890	12,126	7,872
1945	29,529	12,126	7,872	12,929
1946	20,408	7,872	12,929	21,571
1947	11,326	12,929	21,571	23,514
1948	15,890	21,571	23,514	26,879
1949	12,126	23,514	26,879	39,060
1950	7,872	26,879	39,060	46,209
1951	12,929	39,060	46,209	43,528
1952	21,571	46,209	43,528	33,667
1953	23,514	43,528	33,667	35,077
1954	26,879	33,667	35,077	22,285
1955	39,060	35,077	22,285	19,749

-continued-

TABLE 3: American Shad CPUE at time t, t+4, t+5, and t+6
Page 2

Catch Per Unit Effort

Species: American Shad

Year	CPUE (t.)	CPUE (t+4)	CPUE (t+5)	CPUE (t+6)
1956	46,209	22,285	19,749	18,296
1957	43,528	19,749	18,296	15,183
1958	33,667	18,296	15,183	8,512
1959	35,077	15,183	8,512	12,605
1960	22,285	8,512	12,605	7,442
1961	19,749	12,605	7,442	11,605
1962	18,296	7,442	11,605	14,200
1963	15,183	11,605	14,200	15,278
1964	8,512	14,200	15,278	13,178
1965	12,605	15,278	13,178	12,039
1966	7,442	13,178	12,039	19,515
1967	11,605	12,039	19,515	---
1968	14,200	19,515	---	---
1969	15,278	---	---	---
1970	13,178	---	---	---
1971	12,039	---	---	---
1972	19,515	---	---	---
1973				
1974				

Question A 23 d:

With respect to the analysis of stock-recruitment relationships beginning on P. VIII-2:

d. Provide a discussion comparing results for striped bass, white perch, and American shad. Include consideration of factors that may account for the apparent density dependence in the striped bass stock-recruitment relationship but the absence of such apparent density dependence in the white perch and American shad stock-recruitment relationships.

Response:

Statistical evidence of density dependence in the striped bass stock-recruitment relationship was discovered as a result of analysis of data collected specifically to obtain more information about the striped bass fishery. Investigations designed to increase our knowledge of the other two species did not produce similar statistical evidence of this phenomena. This outcome probably is due to;

a) the relatively greater influence of density independent factors as compared with density dependent factors in the data for white perch and American Shad.

b) the possibility of a larger sampling error in the data for these two species, thus producing more scatter,

c) a smaller range of abscissa values in relation to the biologically meaningful range of potential variability for some species, especially white perch,

d) a stock-recruitment relationship characterized by a broad, flat dome closely approximating a zero slope (in the statistical sense) over a broad range of abscissa values (spawning stock density).

Question A 25e:

With respect to the analysis of density-dependent growth beginning on p. VIII-8:

> In light of the apparent relatively high degree of dietary over-lap of young-of-the-year striped bass and white perch (TI, 1973 Annual Report, July 1974, Chapter IV, pp. IV-39 to IV-56), provide analyses of density-dependent growth of striped bass and white perch using as an index of density at Indian Point the mean July-August beach-seine catch per unit surface towed (CPUA) of striped bass and white perch combined.

Response:

The appearance of dietary overlap in these young-of-the-year fish does not by itself merit performing the analyses requested. Examination of Table V-3, p. V-26, indicates that for the years involved, 1965-74, no consistent relationship existed between striped bass and white perch abundances. The results of analyses performed on a combined population would therefore possess a relatively high measure of statistical unreliability, and statements or interpretations based upon these findings would be misleading and inappropriate.

Furthermore, the ecological implications of dietary overlap, have not yet been clearly defined (see p. IV-54, 55, TI 1973 Annual Report). Consequently, the usefulness of analyses restricted to a combined population would be severely limited.

Question A 25f:

With respect to the analysis of density-dependent growth beginning on p. VIII-8:

> The TI analysis of density-dependent growth appears to rely solely on TI data. However, similar beach seine data and growth data have been collected by Lawler, Matusky & Skelly Engineers (LMS) under contracts with Orange & Rockland and Central Hudson. Using these LMS data provide analyses comparable to the TI analyses, as extended by Items a, b, and e above.

Response:

Density-dependent growth analyses similar to those performed by TI will be applied to the data collected by L.M.& S. It will not be possible, however, to submit the results of these analyses before September 1. They will appear in an Environmental Report to accompany Con Edison's application to delete from the license the requirement to terminate operation of the once-through cooling system, which Con Edison extends to file, if justified by the results of the ecological study program, early in 1977.

Question B1:

Provide analyses (including tables and graphs) for the years 1972, 1973, 1974, and 1975 of the temporal distribution (biweekly intervals if available; otherwise monthly intervals) by longitudinal segments for each of the major food items in the diets of young-of-the-year striped bass, white perch, and tomcod.

Question B2:

Provide analyses of food preferences (i.e., electivity indices) for young-of-the-year striped bass, white perch, and tomcod. For striped bass and white perch provide such analyses for the years 1972 and 1973 on a monthly basis for July through November by each size category of young-of-the-year. For young-of-the-year tomcod provide such analyses for 1974 on a monthly basis for May through October.

These questions do not fall within the scope of the Con Edison research program. Samples previously collected for other purposes would not serve as suitable sources for analyses of stomach contents.

PAPER NUMBER

9

Salt Movement Patterns in the Lower Hudson

by

H. J. Simpson
R. Bopp
D. Thurber

Lamont-Doherty Geological Observatory
of Columbia University
Palisades, New York

SALT MOVEMENT PATTERNS IN THE LOWER HUDSON*

H. J. Simpson, R. Bopp, and D. Thurber**

Lamont-Doherty Geological Observatory and Department of Geology of Columbia University, Palisades, N.Y. 10964

Introduction

The most fundamental diagnostic physical parameter of any estuarine system is probably the salinity distribution. The density field established by the salinity distribution, which results from a balance of fresh water influx and turbulent mixing by tidal currents, determines the net non-tidal circulation pattern in an estuary. In addition to controlling net water motion, the salinity distribution is the most critical parameter to the biological community and greatly affects the dynamics of the suspended load.

The Hudson estuary is usually described as a partially mixed estuary, having a continuous northward decrease in salinity in both surface and deep water. Vertical gradients in salinity are usually small, with bottom waters having salinities from 5% to 20% higher than surface waters over most of the salinity intrusion most of the time. The length of the salinity intrusion, and to some extent the vertical salinity distribution, are primarily a function of the input rate of fresh water. During low flows (4000-8000 cfs) the

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length of the salinity intrusion ($\geq$ 100 ppm Cl) is 60-80 miles (Abood, 1972). During extreme conditions of high fresh water flow (50,000-70,000 cfs) saline water can be confined to only the southern 10-15 miles of the estuary.

There have been a number of surveys of the salinity distribution in the Hudson, as well as current meter studies, beginning more than 50 years ago. The implications of the data from these surveys have been summarized and used to develop model descriptions of the net non-tidal two layer circulation (Abood, 1972) and one-dimensional dispersion and advective representations of transport processes in the lower Hudson (NYSDEC, 1970).

Most of the salinity surveys and the attempts to extend the data beyond simple descriptive interpretation have focused on low flow "equilibrium" salinity intrusion conditions, which are typical of summer months when oxygen demand is most critical and when mid-Hudson drinking water supplies are most threatened.

Non-Steady State Salinity in the Hudson

Estuarine salinity distributions in general have substantial temporal variations. Much of the understanding of estuarine circulation is based on studies of large systems, such as Chesapeake Bay (Pritchard, 1953, 1955, 1956). Even large systems such as the Chesapeake show major differences in seasonally averaged salinity patterns (Stroup and Lynn, 1963).

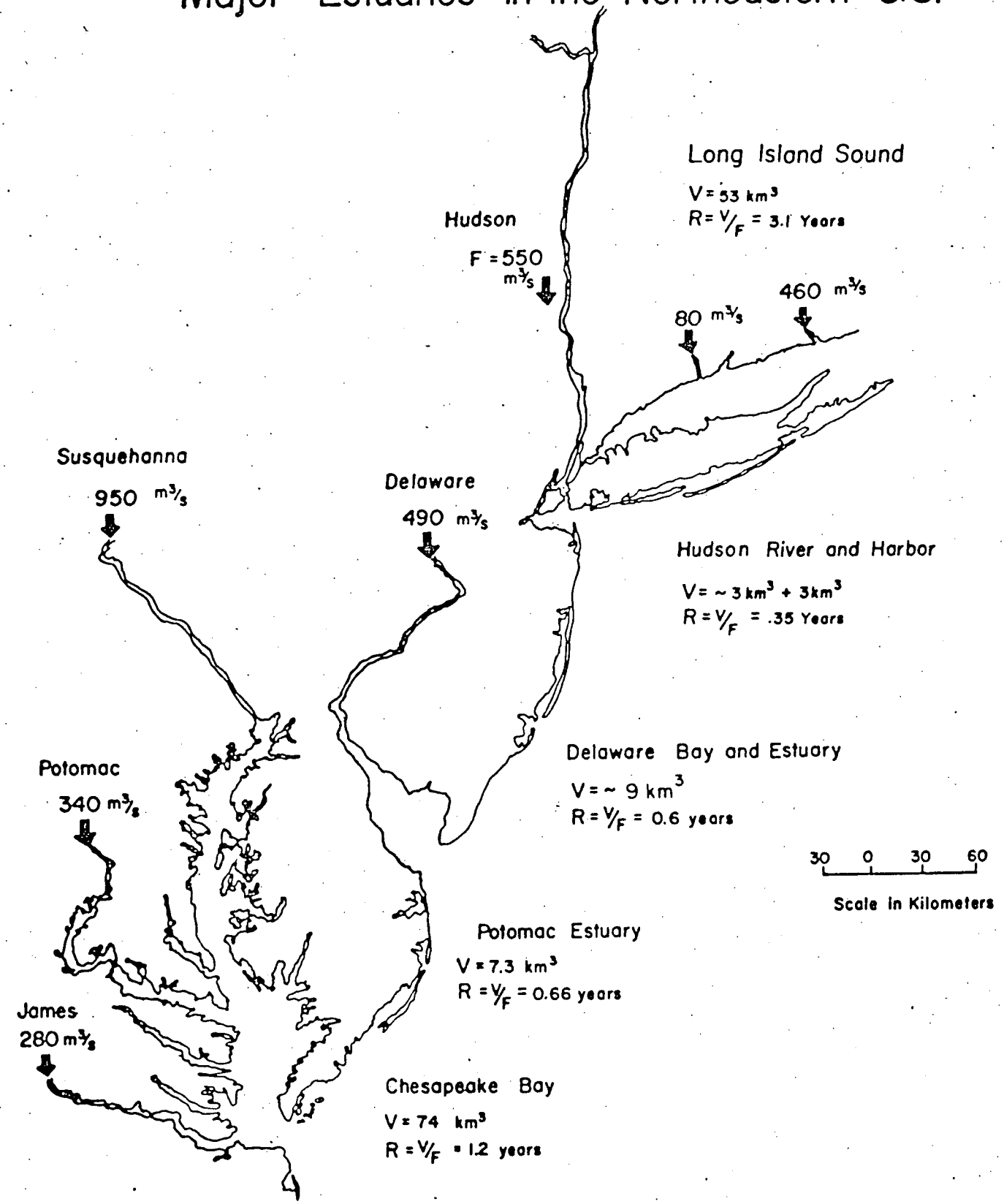
A crude index of the relative stability of an estuary to changes in the salinity distribution is the ratio of the volume of the estuarine system to the mean flow of fresh water into the system. Figure 1 shows the major estuarine systems of the northeastern U.S., with boundaries and volumes somewhat arbitrarily chosen, especially for the Delaware. The volumes indicated include all tidal waters, and not just the regions with measurable salinity intrusion. Long Island Sound is included as a borderline case, although the mean fresh water flow is a very poor indication of the "stability" of that system to salinity changes. It is clear that the Hudson estuary has the lowest ratio of volume to fresh water flow, and hence is the least "stable" with respect to rapid salinity changes.

If the region of the Hudson estuary under consideration is restricted to include only the area showing large seasonal variations in salinity, between the George Washington Bridge (M.P. 11) and Poughkeepsie (M.P. 76), the ratio of volume to mean fresh water flow is only one quarter that shown in Figure 1, which is equivalent to about a one month "flushing" time.

The lack of "stability" in the Hudson becomes even more obvious when the variations in actual flow values, rather than mean annual flows, are considered. The Hudson rarely has a flow equal to its mean annual flow. Mean monthly flows range over more than a factor of five, with a few spring

Figure 1

Major Estuaries in the Northeastern U.S.



months normally having several times the mean annual flow, and half of the other months having 50% or less of the mean annual flow rate (USGS, 1970).

Figure 2 shows a plot of provisional flow data at Green Island for part of 1972 (K. I. Darmer, personal communication). The total flow for this period was substantially greater than average values, especially during May and June, but a pattern of high peak flows with longer periods of relatively low flow is typical. During both May and June, the volume of fresh water entering the Hudson at Green Island was more than three times the volume of the Hudson showing large salinity variations, corresponding to a mean "flushing" time of this region of less than ten days, for a period of more than two months.

It is obviously greatly oversimplified to describe the ratio of volume to fresh water flow in a section of the Hudson as a "flushing" time, but such a presentation does give some indication of how sensitive the geometry of the salinity distribution can be to changes in fresh water input. Some estimation of the rates of and patterns of change which can occur in the Hudson can be gained from simplified mathematical representation of the salinity distribution. One-dimensional diffusion-advection equations are often used to describe the average salinity along the axis of an estuary (averaged over depth, width, and at least one tidal cycle) (NYSDEC, 1970):

Daily Flow of Hudson Green Island
(1972)

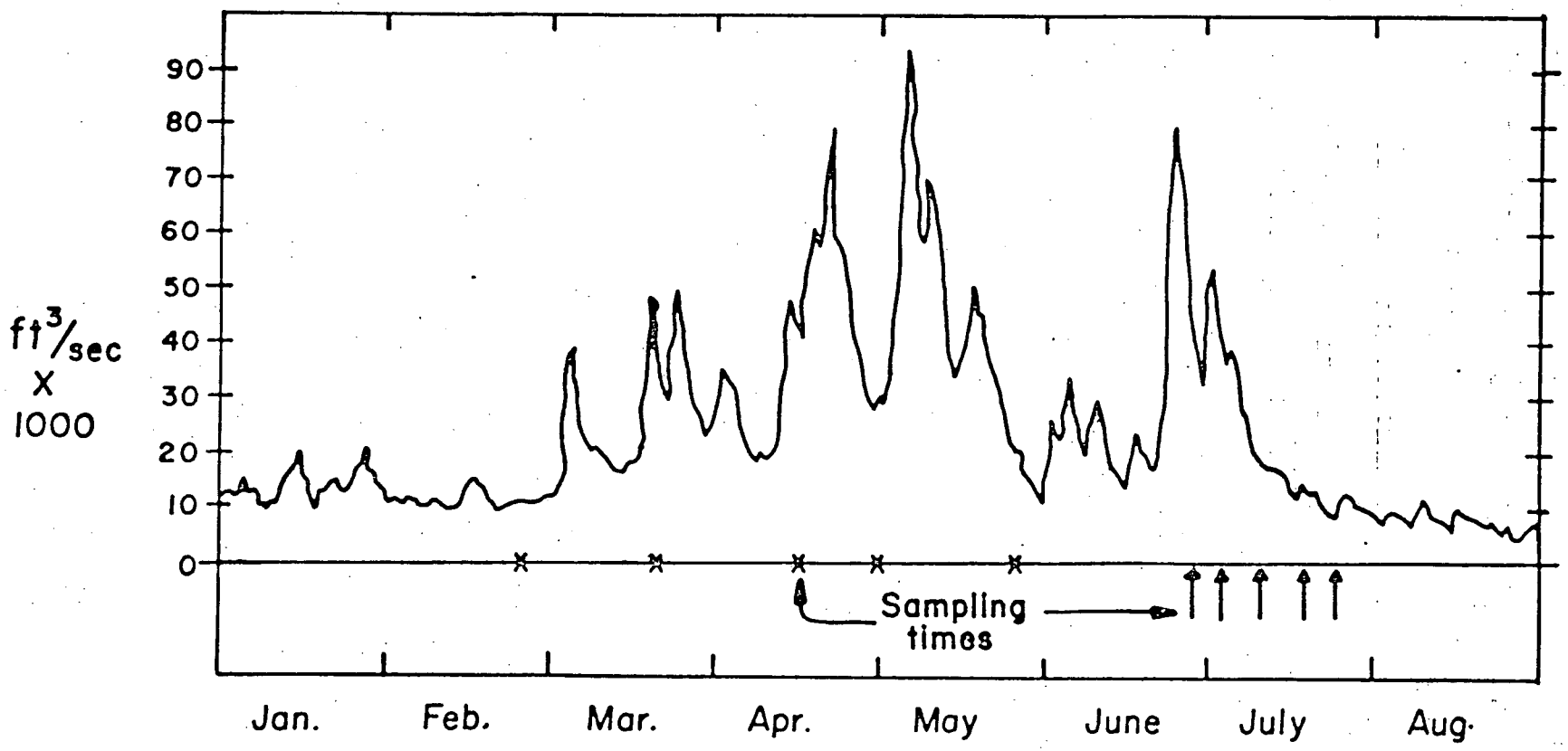


Figure 2

$$\frac{1}{A}\frac{\partial}{\partial x}\left(EA\frac{\partial C}{\partial x} - QC\right) = \frac{\partial C}{\partial t}$$

C = salinity

E = diffusion or "dispersion" coefficient

U = advection rate = Q/A where

Q = fresh water discharge

A = channel cross section

t = time

x = distance along axis of estuary

With steady state conditions ($\partial C/\partial t = 0$) and a limited reach of the estuary to allow the approximation of constant E and constant U, the expression reduces to:

$$E\frac{\partial^2 C}{\partial x^2} - U\frac{\partial C}{\partial x} = 0 \qquad C = C_o\, e^{(U/E)x}$$

Dispersion parameter values can thus be estimated from plots of measured salinity and distance, using an independent estimate of U from extrapolations of upstream gauged flow.

Actual salinity distributions in the Hudson indicate variable dispersion coefficients and numerical models have been employed to describe the salinity distribution more accurately than the simple analytical expression above (NYS DEC, 1970).

The section of the Hudson of primary interest to this paper lies between M.P. 15 and M.P. 45. Over this limited reach, the E values from a low flow numerical model are relatively constant, and average about 10(miles)^2/day (NYS DEC, 1970). The cross sectional area of the Hudson averages

about the same value over this reach, and no major fresh water inputs occur, allowing a constant value for U to be a reasonable approximation. Thus by using the numerical model average value for E and varying U to simulate characteristic fresh water input rates, the distance for the salinity to drop by 1/e can be estimated very simply for this limited reach of the estuary.

Using the approximations of constant E and U, the time dependent diffusion-advection equation can be solved explicitly to examine the time for saline water to approach an equilibrium distribution assuming all of the saline water is initially swept out of the region of interest (M.P. 15-M.P. 45). Such conditions actually do occur during high runoff periods. The time dependent solution is (Harleman, 1966):

$$C(x,t) = \frac{1}{2}C_o\left[\operatorname{erfc}\left(\frac{x-Ut}{\sqrt{4Et}}\right) + e^{(U/E)x} \cdot \operatorname{erfc}\left(\frac{x+Ut}{\sqrt{4Et}}\right)\right]$$

This solution converges to the simple exponential distance relation given earlier for large values of t. A simple approximation of the time dependence of this expression can be made using an exponential with a constant coefficient for time of U^2/E. The time response of this expression is 10-30% slower than the exact solution above, but provides a good approximation.

Using flow values of 1/6, 1/2, and 1 1/2 of the mean flow, we can estimate the equilibrium distance for salinity to drop by 1/e and the time for salinity to reach within 1/e of the equilibrium distribution:

Input Parameters			Salinity Response		
Q^* (cfs)	U (mi/day)	E (mi^2/day)	x (E/U) (miles)	$t(E/U^2)$ (days)	t^{++} (days)
3,000	0.3	10***	30	100	79
9,500	1.0	"	10	10	9
28,000	3.0	"	3	1	0.8
19,000	2.0**	5	2.5	1.3	
"	"	10	5	2.5	
"	"	20+	10	5.0	
"	"	30+	15	7.5	

*mean flow ~19,000 cfs.
**typical of late July 1972.
***average value from low flow model for M.P. 15-45.
+best values for flow conditions in late July 1972 (M.P. 15-45).
++time response for analytical solution (Harleman, 1966): 10-30% faster than simple exponential time approximation (E/U^2).

Thus salinity could decrease from a large percentage of the sea water value to fresh water over only a few miles during high flow, or over 60-80 miles during low flow. The times to reach an equilibrium distribution would be only a few days for high flow, and many months for low flow. These qualitative observations describe the actual response of the salinity

intrusion in the Hudson reasonably well, despite the numerous approximations. During late summer and fall, after several months of low flow (~100 days), the salinity intrusion usually extends several times the distance listed above (30 miles). In contrast, during high flows such as we observed following the passage of tropical storm Agnes in the summer of 1972, saline water was replaced by fresh water over a reach of 10's of miles within a few days, leaving the entire salinity gradient confined to the lower 10-15 miles of the estuary at peak flow.

The variation of E in low flow one-dimensional models which occurs in the reach of the Hudson considered here (M.P. 15-45) is much smaller than the range used in the example (E = 10-30 mi^2/day) while actual variations of U for the Hudson are even larger than the factor of 10 used in the example. Clearly the most critical parameter to determining the equilibrium salinity distribution and the rate of approach to equilibrium is U, the advection coefficient.

Based on this crude mathematical description of the system, the salinity distribution in the Hudson is obviously very sensitive to changes in fresh water input rate, especially during high flow periods. Thus it is essential to observe how the real system actually responds to change in fresh water flow, and then to incorporate the transient mixing characteristics into models which describe the system.

The field measurements of salinity described below were made during a period of highly transient behavior and provide valuable insight into the transport and mixing characteristics of the Hudson.

Salt Movement up the Hudson - Summer 1972

Saline water in the lower Hudson in May and June of 1972 was driven by high fresh water flow far to the south of the normal position of salt advance up the Hudson for these months. Thus salinity conditions were reset to a pattern which probably resembles the period immediately following the normal spring runoff peak. Table 1 lists a series of vertical salinity profiles taken between New York Harbor and the southern boundary of the Tappan Zee. These profiles were taken with an *in situ* induction salinometer, during and immediately following the last peak flow period of the early summer. Some of these data are plotted schematically in Figure 3, adjusted to show their approximate location midway between high water slack and low water slack. At the end of June, the entire Hudson north of the George Washington Bridge was essentially free of saline water.

During the first ten days of July, the location of the boundary between fresh and saline water ($\geq 1‰$) moved northward approximately eight miles. During the next two weeks, the horizontal advance of saline water changed its pattern considerably. South of the Tappan Zee, the boundary between saline and fresh water was very steep, and extended over only

Table 1

SALINITY AND TEMPERATURE PROFILES: NEW YORK HARBOR - PIERMONT PIER

Depth (meters)	m.p. 22.5 June 28 16:00		m.p. 18.3 June 28 16:25		m.p. 11.5 June 28 17:10		m.p. 6.3 June 28 17:50		m.p. -3.0 June 28 18:45		m.p. 14.0 July 3 13:20	
	S (‰)	T (°C)	S (‰)	T (°C)	S (‰)	T (°C)	S (‰)	T (°C)	S (‰)	T (°C)	S (‰)	T (°C)
0											0	21.12
1	0	21.32	0	21.12	0	20.36	0.36	20.00	7.16	19.48		
2											0	21.12
3	0		0		0	20.28	0.52	19.92	9.92	19.28		
4											0	20.88
5	0	20.64	0	20.24	0	20.24	1.60	19.60	12.60	18.96		
6											0	21.20
7	0		0	20.00	0	20.12	4.04	19.12	13.76	18.68		
8											0	21.04
9			0	19.80			5.16	18.84	15.28	18.20		
10	0	20.20									0.28	21.00
11			0	19.80			6.88	18.44	15.52	18.08	0.76	21.04
12											1.40	20.84
13							10.16	18.20			2.08	20.80
14											2.16	20.96
15							12.60	17.84	16.64	18.08	2.20	20.84
16											2.64	20.64
17							12.84	17.84	22.40	16.72	2.80	20.64
18												
19												
20							12.72	17.84				

	m.p. 16.0 July 3 14:10		m.p. 14.0 July 10 12:30		m.p. 16.0 July 10 13:20		m.p. 18.0 July 10 13:50		m.p. 18.0 July 18 11:35		m.p. 21.6 July 18 13:30	
	S (‰)	T (°C)	S (‰)	T (°C)	S (‰)	T (°C)	S (‰)	T (°C)	S (‰)	T (°C)	S (‰)	T (°C)
0	0	21.28										
1			4.96	21.56	2.34	22.08	0.12	21.60	0	24.44	0	24.60
2												
3			5.52	21.16	2.80	21.20	0.16	21.44	0.32	24.12	0	24.44
4	0											
5			5.88	20.88	4.56	20.72	0.36	21.00	2.00	23.68	0	24.32
6												
7			7.32	20.44	4.88	20.60	0.88	20.84	7.52	22.48	2.48	23.24
8	0											
9			8.08	20.40	5.12	20.52	1.52	20.80	10.04	21.84	4.72	22.64
10	0											
11			8.40	20.36	5.16	20.56	1.60	20.80	11.48	21.64	6.76	22.32
12	0	21.20										
13			8.56	20.32	5.24	20.52	1.84	20.96	12.40	21.28	8.32	22.04
14	0								12.32	21.60	8.68	21.96
15			8.84	20.32	5.24	20.52	2.00	20.92			8.88	21.84
16	0	21.16					2.04	20.84			9.04	21.84
17											9.20	21.80

Northward Movement Salt — Hudson River 1972

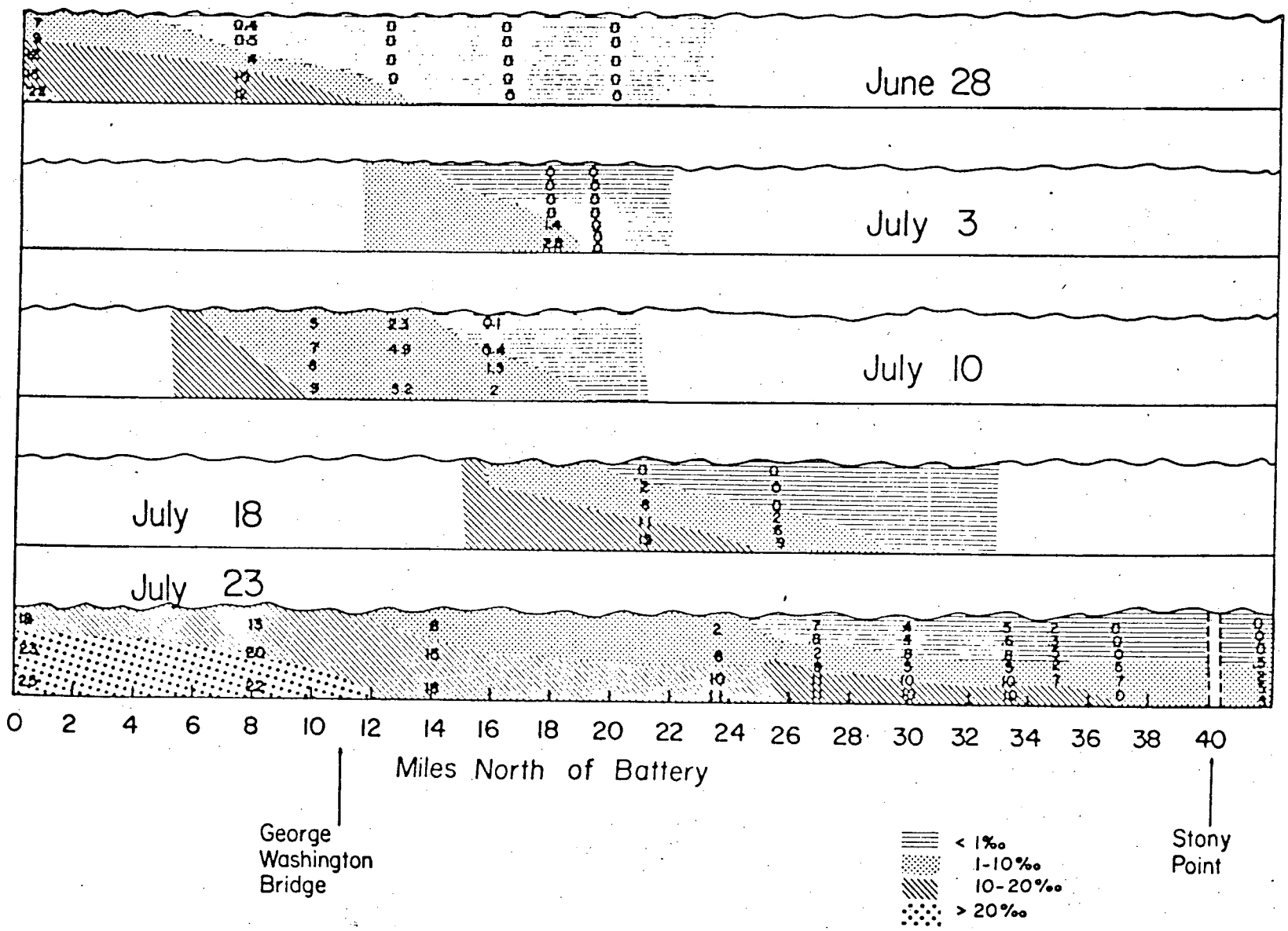


Figure 3

a few river miles. As the salt wedge pushed into the Tappan Zee, the morphology and rate of northward advance were dramatically changed. The saline water advanced along the bottom few meters of the navigation channel, with little mixing with the overlying fresh water. Representative salinity profiles are given in Table 2, and plotted schematically in Figure 3. The approximate time sequence and mode of advance of saline water are shown in Figure 4. Thus during the first two weeks of this period, saline water advanced northward only about eight miles (Mile Point [M.P.] 11 to M.P. 19), contrasted with about twenty-four miles (M.P. 19 to M.P. 43) during the next two weeks. The flux of salt northward past any point near the "salt front" in these two periods, however, was comparable. The average total cross sections of the river in the two regions are similar, but only 1/6 to 1/3 of the total cross section in the Tappan Zee-Haverstraw Bay area was actually involved in the bulk of the northward movement of salt.

The observations crudely fit an advection parameter of 2 miles/day (consistent with the gauged flow during this period) and a dispersion parameter of 20-30 miles squared per day, which is 2-3 times that of low flow periods for this reach of the estuary. In this case, it is not possible to obtain a really good fit of one-dimensional model parameters, which suggests that two layer models will probably be required for more accruate description of transient high flow condi-

Table 2

SALINITY PROFILES: PIERMONT PIER - BEAR MOUNTAIN BRIDGE

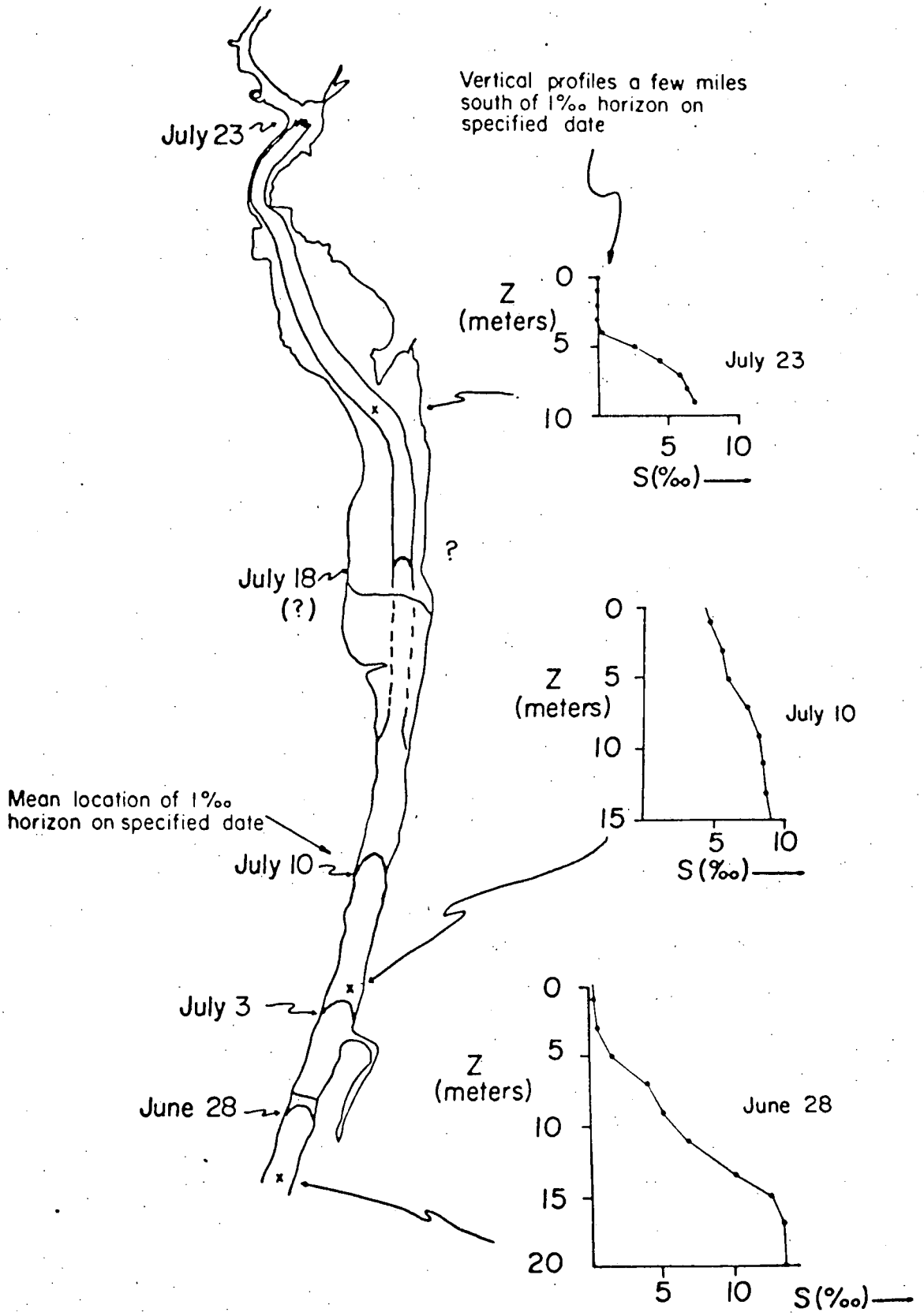
Depth (meters)	S (‰)	S (‰)	S (‰)	S (‰)	S (‰)	S (‰)	S (‰)	S (‰)	S (‰)	S (‰)
m.p.	24.9	25.0	27.0	29.3	31.2	33.0	35.0	34.0	37.0	38.6
	July 22, 1972							July 23, 1972		
	12:00	13:55	14:25	14:47	15:09	15:37	16:07	19:13	19:33	19:54
0	.40	0	0	0	0	0	0	0.56	0.36	0.00
1					0	0				
2	.88	0	0	0	0	0	0	0.60	0.48	0.44
3					0.36	0				
4	2.24	0.20	0	0.48	1.00	0.32	0	0.80	1.88	0.76
5				1.28	2.00	2.68	0.08	3.00	2.76	0.88
6	4.16	1.16	2.44	2.48	4.00	4.40	0.60	4.96	6.36	
7			5.84	7.04	6.84	5.40	0.88	6.24	7.52	1.36
8	4.56	8.96	8.44	9.08		6.32	2.36	7.64		2.44
9				9.48		6.88	5.12		8.04	6.60
10	4.72	10.44	10.08				5.44	8.20		6.60
11									8.04	6.88
12		10.84	9.92							

Depth (meters)	S (‰)	S (‰)	S (‰)
	40.2	40.2	46.0
	July 23, 1972		
	12:10	20:15	21:50
0	0.12	0	0
2	0.16	0.44	
4	0.24	0.44	0
6	0.40	0.44	
8	0.56	0.44	
10	0.56	0.44	
12	0.80		
14	2.40	0.92	0
16	2.72		
18	2.80		
20	2.84	2.00	
22	3.28		
24	3.64	3.44	0.20
26	4.44	3.88	
28	4.88	4.32	
30	4.88		
32			
34			0.28
36			
38			
40			
42			
44			0.80

Depth (meters)	July 23, 1972				
	15:35	16:01	16:25	16:49	17:10
0	0.72	0.36	0.48	0.24	0
1				0.32	0
2	0.76	0.36	0.60	0.52	0
3				1.04	0.40
4	1.08	0.80	0.76	1.40	2.56
5				2.52	3.68
6	2.04	4.00	2.12	5.04	5.28
7	4.40	5.92	5.24	6.88	7.20
8	7.24	9.56	7.44		7.92
9	9.60		9.56		
10		10.08	9.72		9.08
11	10.80	10.16			
12					
13	10.88				

Figure 4

Salt Front (1‰) Movement Up The Hudson (1972)



tions, especially in the Tappan Zee and Haverstraw Bay.

Other Evidence of Salt Wedge Movement

Observations during other periods also indicate that a well developed high salinity layer in the Tappan Zee-Haverstraw Bay area is not uncommon during and after high fresh water flows. On Figure 2, several arrows are drawn to indicate the times of sampling for the salinity profiles described above. Data from several earlier periods were also obtained, as indicated by x's on Figure 2. These salinity profiles (Tom Malone, CCNY, unpublished data) taken at a few locations during the winter and early spring, 1972, also indicate rapid salt movement up and down the Hudson in response to changing fresh water flow. The data are shown schematically in Figure 5, with another set of unpublished data from the Harbor region (David Jay, SUNY Stony Brook, unpublished data). The profiles from April 16 indicate another period with a high salinity layer in the navigation channel of Haverstraw Bay.

A few profiles taken before and after high runoff periods in September 1971 also indicate a high salinity layer in the navigation channel in the Tappan Zee (Simpson, unpublished data).

Mixing at the Southern Boundary of the Highlands

Salinity profiles in the Hudson during low flow periods show little vertical gradient, and most of the time do not show a two layer structure as well defined as that found in

Salinity Distribution —— Winter - Spring 1972

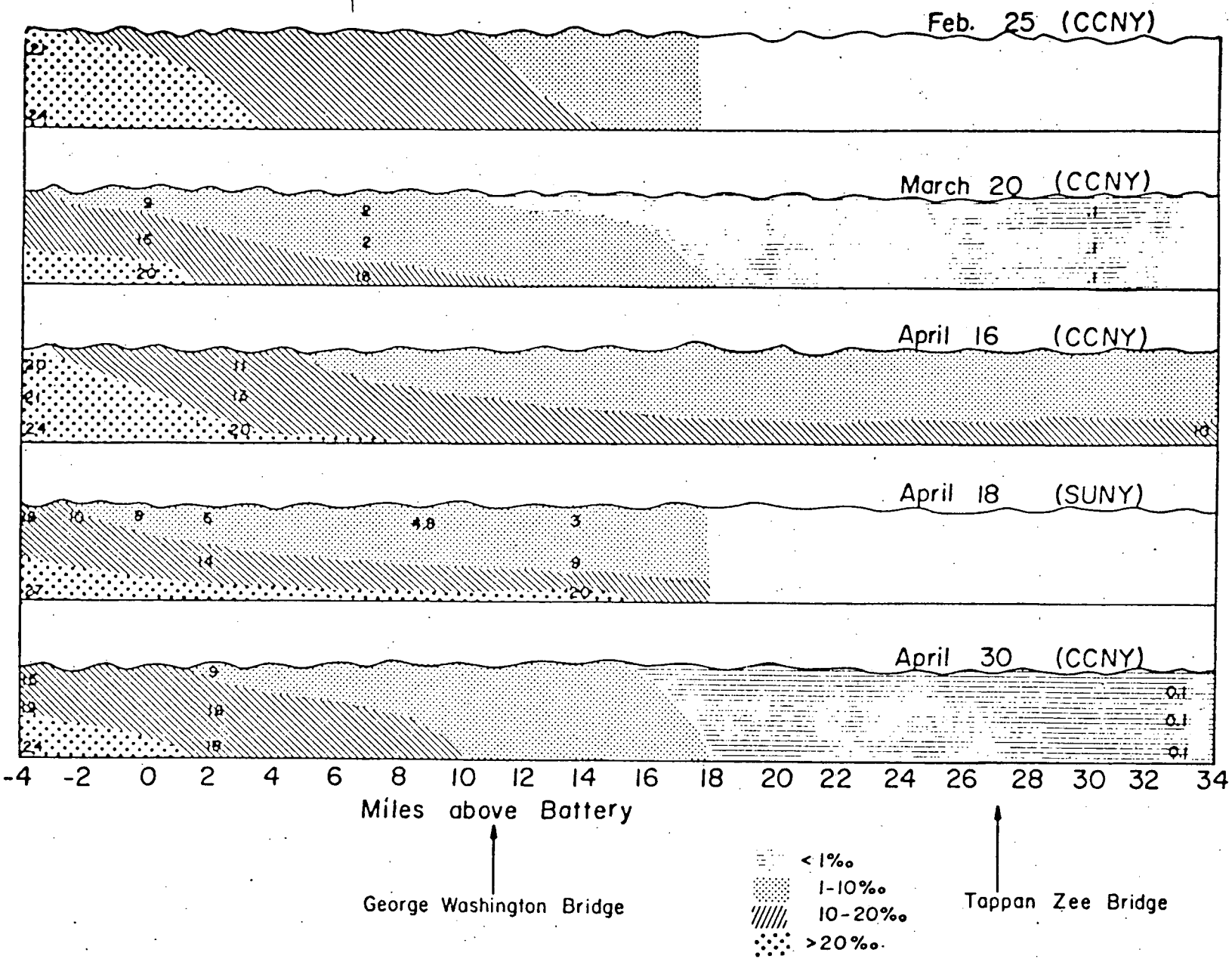


Figure 5

the Tappan Zee-Haverstraw Bay area during July 1972. There clearly must be efficient vertical mixing processes to destroy the type of circulation set up after periods of high fresh water runoff. One of the most critical regions to vertical mixing is apparently the area near the southern boundary of the Hudson Highlands (M.P. 40-44), where the first major increases in water depth occur, as saline water advances northward. This area is very unusual in the estuarine regions of the northeast, since depth commonly decreases slowly in an upstream direction. The sudden increase in channel depth in the Hudson is quite dramatic, going from a relatively flat 10-12 meters to an average value of nearly 30 meters with large changes in channel depth both above and below the mean level. During the period of rapid northward movement of a saline layer through Haverstraw Bay, a number of salinity profiles were collected over a tidal cycle, near the southern boundary of the Highlands at Tompkins Cove (M.P. 41). These data are given in Table 3, and plotted in Figure 6. These profiles were measured immediately following those showing a high salinity bottom layer to the south.

During the first few hours of upstream current, salinity profiles showed a large vertical gradient, and increasing salinity for each succeeding profile (Figure 6, A). After high water slack, the salinity began to decrease, and the vertical gradient to decrease (Figure 6, B). By four hours after slack, the vertical gradient was entirely gone, and the next three hours showed steadily decreasing salinity,

Table 3

SALINITY AND TEMPERATURE DEPTH PROFILES - TIDAL CYCLE AT TOMPKINS COVE, N. Y.

July 23-24, 1972

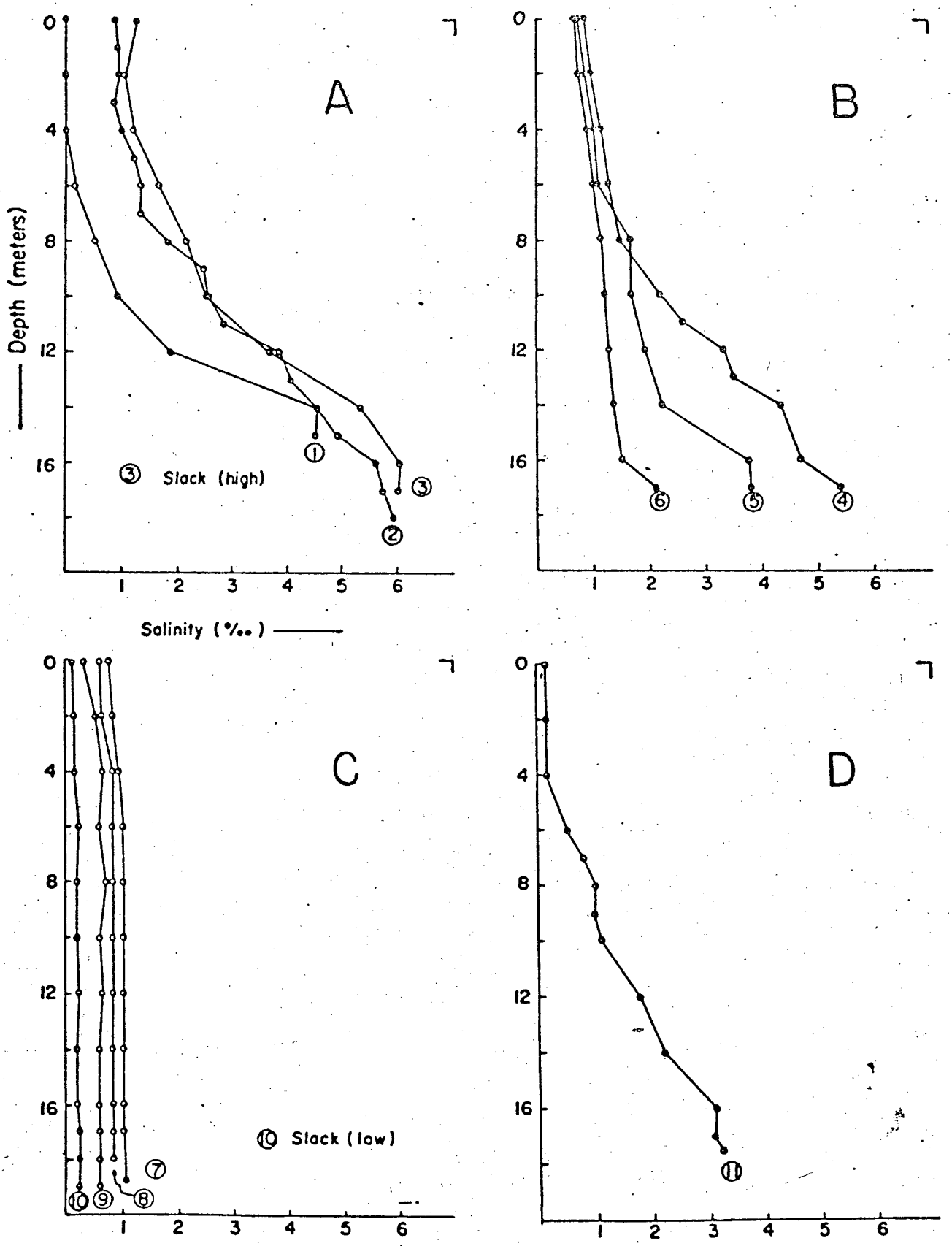
Depth (meters)	(1) S (‰)	(1) T (°C)	(2) S (‰)	(2) T (°C)	(3) S (‰)	(3) T (°C)	(4) S (‰)	(4) T (°C)	(5) S (‰)	(5) T (°C)	(6) S (‰)	(6) T (°C)
0	0.00	24.76	0.88	25.20	1.28	27.20	0.84	25.88	0.72	25.76	0.68	25.28
1			0.92	25.12								
2	0.00	24.56	0.96	25.16	1.08	25.72	0.96	25.40	0.84	25.24	0.72	25.20
3			0.88	25.08								
4	0.00	24.64	1.00	24.92	1.20	25.36	1.12	25.44	1.00	25.20	0.88	24.92
5			1.20	24.84								
6	0.16	24.60	1.32	24.92	1.68	25.40	1.28	25.28	1.08	25.20	1.00	24.84
7			1.32	24.88								
8	0.52	24.56	1.80	24.80	2.16	25.20	1.48	25.12	1.68	24.72	1.16	24.84
9			2.48	24.84								
10	0.92	24.56	2.56	24.44	2.52	25.04	2.20	25.08	1.68	24.72	1.20	24.80
11			2.84	24.40			2.60	24.88				
12	1.88	24.44	3.84	24.20	3.68	24.72	3.32	24.60	1.92	24.64	1.28	24.64
13			4.04	23.76			3.48	24.60				
14	4.52	24.08	4.56	23.80	5.36	24.32	4.32	24.48	2.20	24.56	1.36	24.60
15	4.48	23.76	4.92	23.64			4.52	24.48				
16			5.64	23.56	6.08	24.08	4.68	24.28	3.76	24.40	1.52	24.52
17			5.76	23.60	6.04	24.12	5.40	24.16	3.80	24.16	2.12	24.48
18			5.96	23.72								

Depth (meters)	(7) S (‰)	(7) T (°C)	(8) S (‰)	(8) T (°C)	(9) S (‰)	(9) T (°C)	(10) S (‰)	(10) T (°C)	(11) S (‰)	(11) T (°C)
0	0.80	24.80	0.64	24.36	0.36	24.52	0.16	24.64	0.16	24.56
1										
2	0.84	24.72	0.68	24.40	0.56	24.48	0.16	24.48	0.16	24.52
3										
4	0.96	24.68	0.84	24.40	0.68	24.48	0.16	24.48	0.16	24.48
5										
6	1.04	24.64	0.84	24.36	0.60	24.48	0.24	24.56	0.52	24.44
7									0.80	24.40
8	1.04	24.56	0.84	24.44	0.72	24.52	0.20	24.44	1.00	24.40
9									1.00	24.44
10	1.04	24.52	0.82	24.44	0.60	24.52	0.20	24.44	1.12	24.44
11										
12	1.04	24.60	0.84	24.48	0.64	24.48	0.24	24.48	1.80	24.40
13										
14	1.04	24.68	0.84	24.48	0.60	24.44	0.20	24.52	2.24	24.44
15										
16	1.04	24.68	0.84	24.44	0.60	24.36	0.20	24.44	3.12	24.32
17	1.04	24.60	0.84	24.44	0.60	24.44	0.24	24.40	3.08	24.28
18			0.84	24.44	0.60	24.36	0.24	24.40	3.24	24.24
19	1.08	24.68			0.60	24.40	0.24	24.44		

(1) 20:42-20:55
(2) 23:20-23:33
(3) 00:30-00:43
(4) 01:25-01:40
(5) 02:35-02:50
(6) 03:28-03:43
(7) 04:30-04:45
(8) 05:35-05:50
(9) 06:30-06:50
(10) 07:30-07:45
(11) 08:33-08:45

Figure 6

Salinity Profiles — Tidal Cycle
Tompkins Cove July 23-24, 1972



with almost perfectly uniform vertical salinities (Figure 6, C). One hour after low water slack, the strong vertical gradient was reestablished as high salinity water advanced along the bottom (Figure 6, D). Based on these profiles, it appears that the vertical mixing in the region a few miles north of Tompkins Cove (M.P. 41) must be extremely intense, essentially destroying the layered structure moving northward.

A salinity profile taken just south of Bear Mountain Bridge (M.P. 46) is shown in Table 2. This profile, taken during the period of the tidal cycle measurements made at Tompkins Cove, shows a very small gradient over the entire 44 meter water column, less than five miles north of an area with a well defined two layer structure. It is clear that the vertical mixing in this region is very strong.

The dramatic change in the character of vertical salinity profiles during one tidal cycle at Tompkins Cove did not occur at two sites well to the south of the Highlands southern boundary. Vertical profiles of salinity were taken in mid-channel opposite Piermont Pier and Spuyten Duyvil (a few miles north of the George Washington Bridge) through a tidal cycle within 24 hours of the profiles measured at Tompkins Cove. The data are listed in Table 4 and plotted in Figure 7. In both cases, there is no dramatic change in the character of vertical profiles through a tidal cycle, indicating that the intense vertical mixing observed at Tompkins Cove was not

Table 4

SALINITY AND DEPTH PROFILES - TIDAL CYCLE OFF PIERMONT PIER, N. Y.

July 24, 1972

Depth (meters)	(12) S (‰)	(12) T (°C)	(13) S (‰)	(13) T (°C)	(14) S (‰)	(14) T (°C)	(15) S (‰)	(15) T (°C)	(16) S (‰)	(16) T (°C)	(17) S (‰)	(17) T (°C)
0	1.5	26.7	2.0	26.6	1.6	26.5	1.4	26.4	1.3	26.3	1.8	26.8
1												
2	2.3	26.0	2.0	26.6	1.6	26.5	1.4	26.4	1.5	26.4	2.0	26.9
3			3.0	25.7	1.8	25.8						
4	8.4	24.2	4.4	25.4	1.9	26.3	1.6	26.1	2.2	26.0	4.5	25.2
5	8.6	24.2	7.7	24.3	2.0	25.9	1.8	26.2				
6					4.8	24.7	4.3	25.2	3.8	25.2	10.3	23.4
7	10.3	23.4	9.8	23.6	7.3	23.9	6.5	24.5	6.1	24.6		
8							8.2	23.9	10.0	23.4	10.8	23.1
9	11.0	23.2	10.6	23.1	10.2	23.0						
10							9.9	23.2	10.2	23.2	11.2	23.0
11	11.2	23.2	10.8	23.2	10.6	22.8						
12							10.1	23.0	10.3	23.2	11.2	23.0
13	11.2	23.2	10.9	23.0	10.6	22.8			10.3	23.2	11.2	23.0
14			10.9	23.1	10.8	22.9						
15												

SALINITY AND DEPTH PROFILES - TIDAL CYCLE AT SPUYTEN DUYVIL, N. Y.

July 24-25, 1972

Depth (meters)	(18) S (‰)	(18) T (°C)	(19) S (‰)	(19) T (°C)	(20) S (‰)	(20) T (°C)	(21) S (‰)	(21) T (°C)
0	6.2	26.0	8.1	25.4	9.8	24.7	5.0	25.2
1								
2	6.7	25.8	8.9	25.2	9.8	24.6	6.5	25.0
3								
4	7.6	25.3	9.8	24.8	15.2	23.1	10.6	23.9
5								
6	8.4	25.2	11.6	24.0	15.2	23.1	13.8	23.4
7			15.0	23.2				
8	13.8	23.4	17.0	22.3	18.5	22.0	15.4	22.6
9								
10	15.7	22.7	17.5	22.3	18.5	21.9	15.8	22.6
11								
12	16.4	22.2	17.6	22.1	18.9	21.9	15.9	22.5
13								
14	16.9	22.2			18.9	21.8	15.8	22.5
15	17.1	22.1						

Piermont Pier

(12) 11:30-11:40
(13) 13:00-13:10
(14) 14:10-14:20
(15) 15:10-15:20
(16) 16:30-16:40
(17) 18:15-18:25

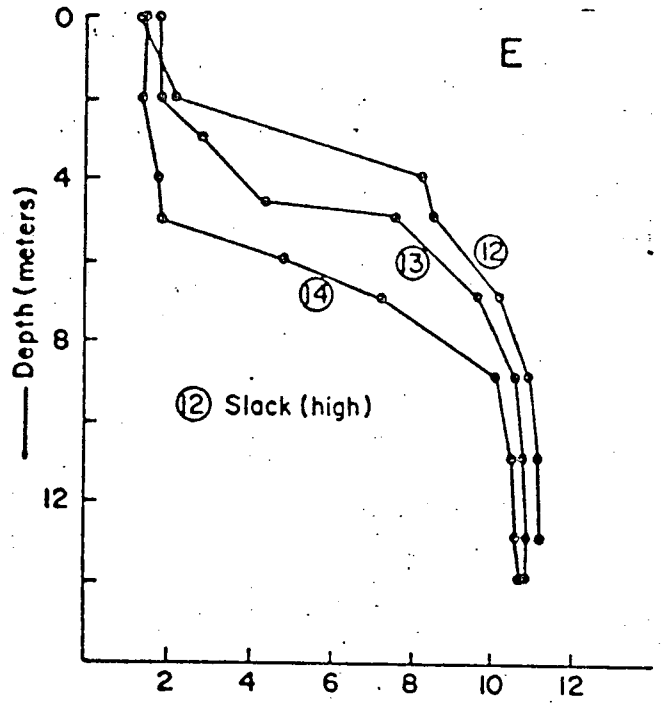
Spuyten Duyvil

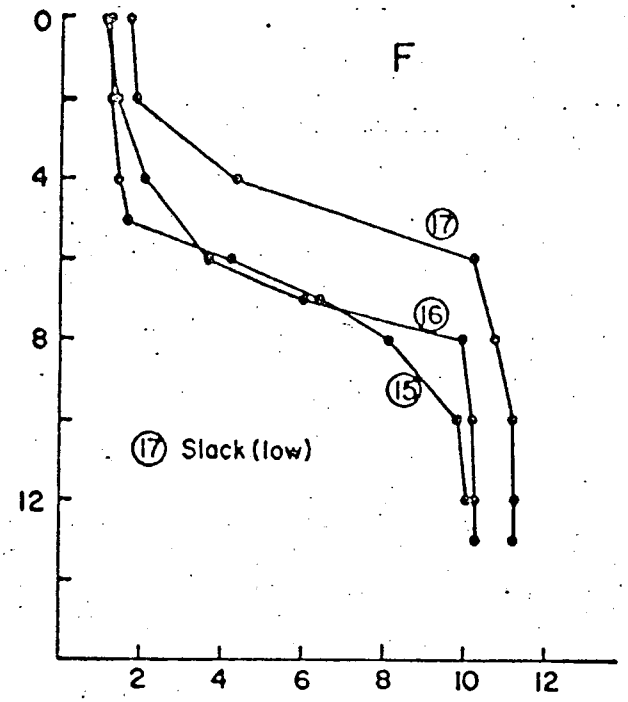
(18) 20:15-20:25
(19) 21:35-21:45
(20) 22:45-22:55
(21) 07:30-07:40

Figure 7

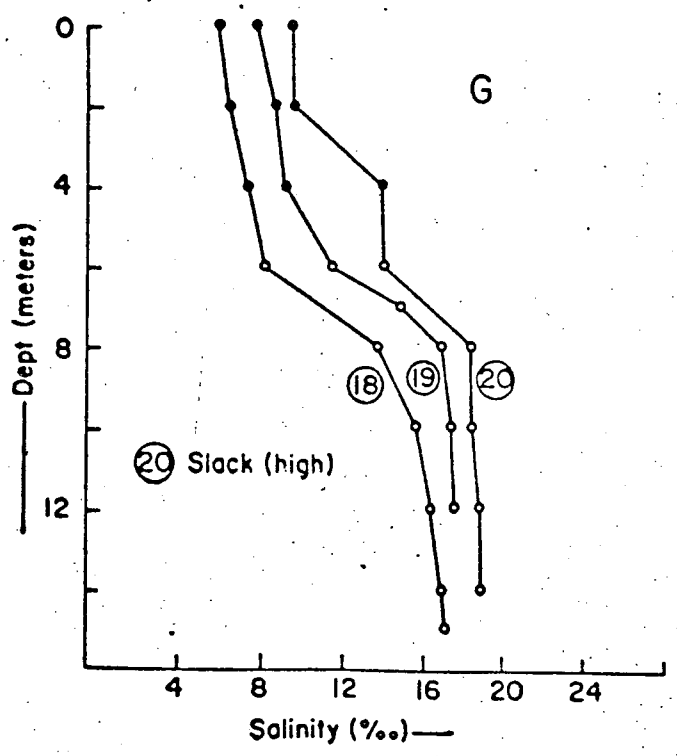
Salinity Profiles — Tidal Cycles

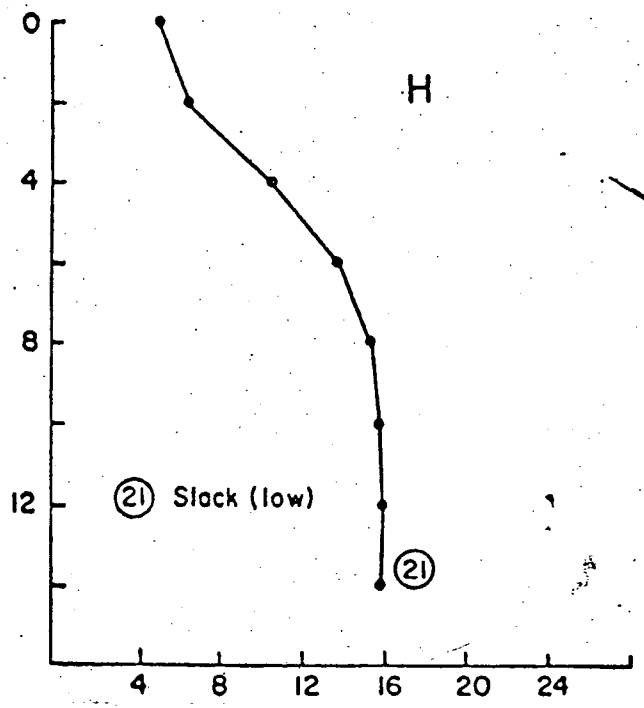
Piermont Pier July 24, 1972





Spuyten Duyvil July 24-25, 1972





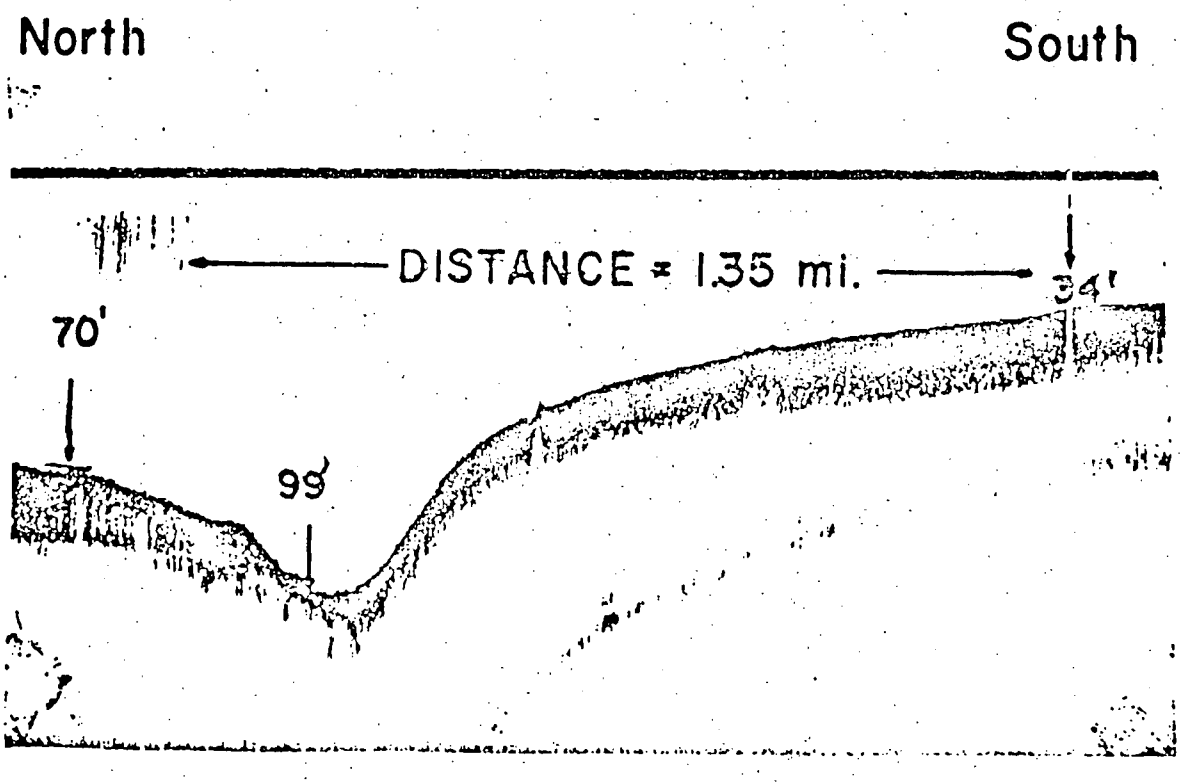
typical of other regions in the estuary during this period. Vertical gradients are considerably smaller at Spuyten Duyvil (Figure 7, G-H) than at Piermont Pier (Figure 7, E-F), but neither locality shows the rapid temporal change observed at Tompkins Cove.

Mixing near Stony Point

The first deep hole in the Hudson north of Haverstraw Bay is located opposite Stony Point (H.P. 40). The bottom drops rapidly from about 11 meters to more than 30 meters, and then comes back up to approximately 20 meters. A depth recorder trace taken in this region is shown in Figure 8. Several salinity profiles were taken in the center of this hole and are shown in Table 2. Two profiles, taken approximately eight hours apart, showed striking similarity, and contrasted strongly with the two layer structure to the south and to the north, shown in Tables 2 and 3. Most of the saline water to the south was confined to a layer only two or three meters deep, while the same salinity values were stretched over five meters within the hole. The contrast in these two types of profiles gives a graphic demonstration of the vertical mixing which occurs in a saline layer as it descends into a portion of the channel with a marked increase in depth.

The most curious finding in the Stony Point area was that a salinity profile taken more than a mile to the north, less than 30 minutes after one taken in the hole at Stony Point, in a much shallower area, showed a strong vertical gradient

BOTTOM TOPOGRAPHY AT STONY POINT



- Midchannel Section
- Depth Recorder Tracer With Net Velocity 5.75 Knots

Figure 8

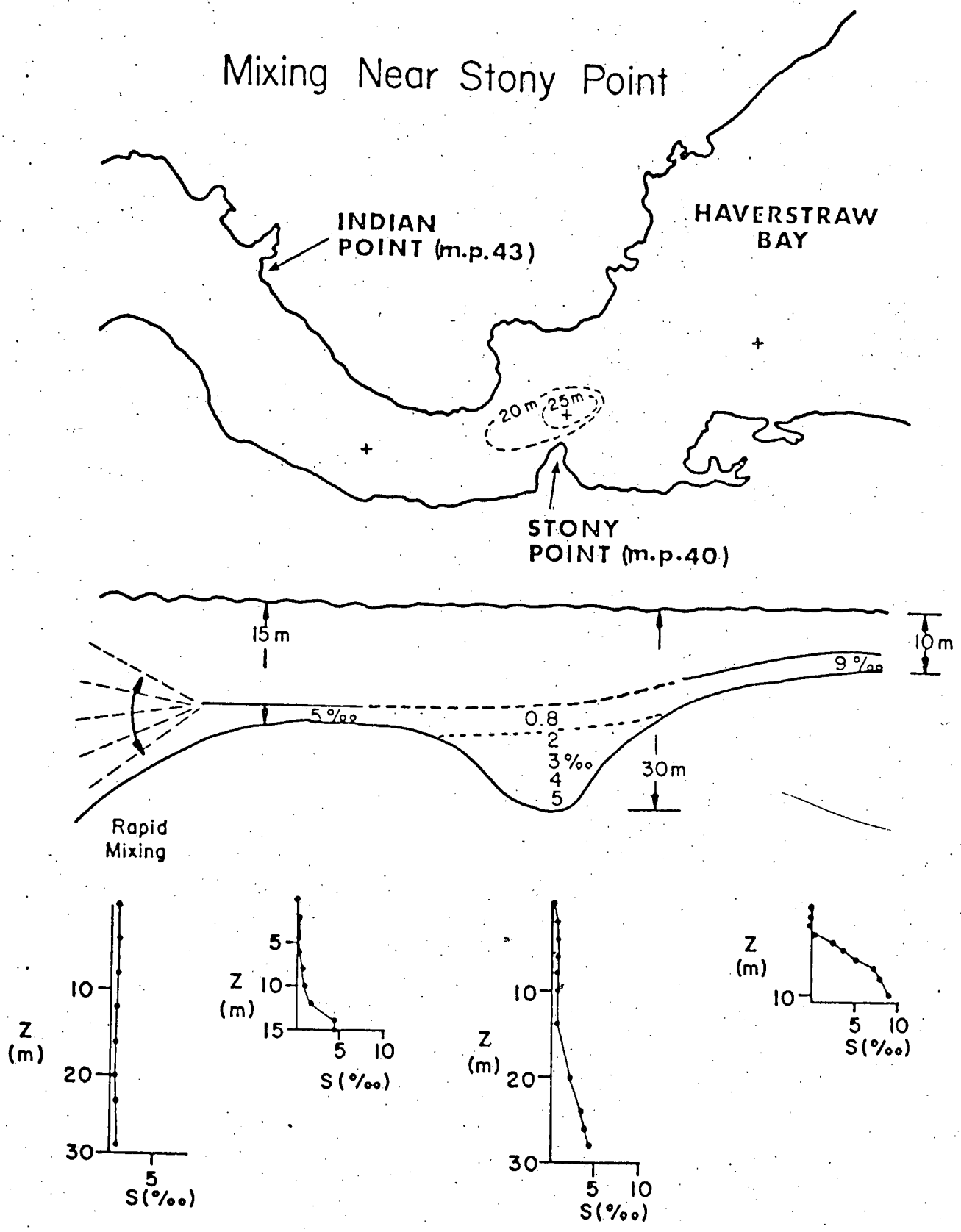
and an isohaline layer near the bottom. These profiles were both taken during upstream flow of water. It is clearly impossible for saline water to "unmix" and return to a layered structure after moving through the hole at Stony Point. One plausible explanation is that a substantial portion of the flow must go around the deepest part of the channel, avoiding vertical mixing of the bottom saline layer as it passes Stony Point.

Figure 9 shows some representative profiles taken in the region including both Stony Point, and the area of rapid vertical mixing at the Highlands boundary. A sketch of the location of a saline layer near the bottom both above and below Stony Point is shown. All of the salinity profiles shown in Figure 9 were collected within a few hours, during flood tide (except the profile furthest to the north, which was taken several hours after ebb began).

All the salinity data reported here were taken with an *in situ* induction salinometer. A number of water samples were collected with 30 liter Niskin bottles while the salinity profiles were being taken. Chloride determinations on the large water samples usually were within ±5% of the *in situ* salinity reading, except for readings of less than 1‰, where the *in situ* readings were usually 0.3 to 0.5‰ lower than those calculated from laboratory chloride measurements. Hence, some of the values reported as "0" in the tables probably indicate conditions where the upper meter of water

Figure 9

Mixing Near Stony Point



averaged up to 0.5‰. The minimum chloride value observed was about 9 ppm. During the period of these observations, most of the salinity gradients measured were quite large in vertical profiles, as well as along the axis of the estuary. All of the data reported here were taken from the deepest part of the channel. Several profiles were taken across the width of the estuary, and no significant differences were observed across, except in the Tappan Zee-Haverstraw Bay area where no bottom high salinity layer was observed outside the navigation channel, and near surface salinities were lower away from the channel.

Summary and Conclusions

Salinity measurements made in critical regions of the Hudson can give valuable information about the time scale and pattern of both horizontal and vertical mixing. Saline water moves back into the lower Hudson between M.P. 11 and M.P. 43 quite rapidly after the area is swept free by high fresh water flow. The northward advance of saline water through the wide, shallow region of the river north of the New York-New Jersey line can sometimes occur primarily along the bottom two or three meters of the navigation channel. During such a period, mixing upward and laterally in this region occurs on a much slower time scale. Thus this region can show substantial vertical and horizontal inhomogeneity following periods of high runoff.

A crude attempt to relate the rapid northward transport of salt to one-dimensional model parameters was made. The saline layer (S = 10‰) in the Tappan Zee and Haverstraw Bay was assumed to be well mixed vertically with the low salinity layer ($\leq$ 1‰) and the advection parameter was estimated from the Green Island records (Figure 2) and both the dispersion (E) and advection (U) coefficients were allowed to vary. It was not possible to fit both the time response and the horizontal gradient of the depth averaged salinity to a single pair of parameters. The closest approximation was to use the best estimates of U from the flow data (2.0 mi/day) and a value of E between 20 and 30 mi^2/day, approximately 2-3 times the low flows estimates of E for this reach of the estuary. Some experimental evidence (cited in Harleman, 1966) suggests that apparent diffusion coefficients determined by dye diffusion experiments increase by approximately a factor of 3 over constant density experiments where there is a density contrast of about 1% (slightly more then existed in the Hudson between the two layers of flow). Thus the observations of transient upstream movement of saline water suggest a pattern and rate of transport which is significantly different from low flow conditions, primarily in the reach between M.P. 20 and M.P. 45.

The deepening of the channel north of Haverstraw Bay induces strong vertical mixing, and dramatically alters any two layer structure entering from the south. The most critical

region to strong vertical mixing occurs within a few miles of mile point 44. North of this area, the salinity intrusion pattern seems to be reasonably well described by low flow one-dimensional model parameters.

It is not unlikely that the pattern of northward movement observed in July 1972 will follow periods of high fresh water runoff of sufficient magnitude, probably occurring at least once each year following the peak flow during the spring.

The pattern of mixing, both horizontal and vertical, has substantial implications for uses of the river in the region between M.P. 20 and 45. The mixing pattern near the southern boundary of the Highlands must be clearly defined, considering the current heavy use of that region for power plant cooling and the potential for strong interaction with biological systems there. The movement of water northward from Manhattan also affects recreational areas to the south of the Highlands. The closing of many public beaches in this region is, at least in part, the result of northward transport of water with high coliform counts. Proper management of the lower Hudson clearly demands accurate information about both transient and "steady state" mixing patterns in the river.

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cheerful cooperation, and the City University for providing us with the opportunity to participate in this cruise. We also thank Bruce Deck of Lamont-Doherty for providing a large number of chloride analyses.

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List of Figure Captions

Fig. 1. Morphology, volumes and mean annual fresh water flows of the major estuaries in the northeastern United States.

Fig. 2. Provisional daily flow volumes of the Hudson River at Green Island, New York, 1972. Times of salinity sampling in the lower Hudson shown with arrows and x's.

Fig. 3. Schematic salinity profiles in the lower Hudson; June-July 1972. Time sequence shows progressive northward movement of saline water.

Fig. 4. Schematic representation of the approximate location of the 1‰ salinity horizon with time, showing pattern and rate of saline water advancing northward in the Hudson.

Fig. 5. Salinity distribution during periods of variable, high fresh water flow during the winter and spring of 1972. Pattern based on more tightly controlled data from Figure 3.

Fig. 6. Tidal cycle salinity profiles taken near the southern boundary of Hudson Highlands. Numbers indicate time sequence, with approximately one hour between each profile (except between 1 and 2, where the interval was three hours). Pattern shows intense vertical mixing north of sampling site.

Fig. 7. Tidal cycle salinity profile taken in mid-channel off Piermont Pier and Spuyten Duyvil. Numbers indicate time sequence, with approximately one hour between profiles at each locality, except between profiles 20 and 21.

Fig. 8. Depth recorder trace of deep depression in the Hudson Channel opposite Stony Point.

Fig. 9. Schematic description of the pattern of vertical mixing in the region between mile points 39 and 45, with representative salinity profiles from several locations.