State of Maryland

BOARD OF NATURAL RESOURCES

A Study Of Water Quality In Baltimore Harbor

Chesley F. Garland

September, 1952

Publication No. 96

Chesapeake Biological Laboratory

Department of Research and Education

Solomons Island, Maryland

State of Maryland

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ACKNOWLEDGMENTS

This report is based on a study sponsored by the Chesapeake Biological Laboratory of the Maryland Department of Research and Education. The work was carried on at The Johns Hopkins University under the Department of Sanitary Engineering and Water Resources. The assistance of the many individuals who contributed generously of their time and abilities to this investigation is acknowledged gratefully.

Special thanks are due Dr. Abel Wolman, Dr. John C. Geyer and Dr. Charles E. Renn of the Department of Sanitary Engineering and Water Resources for their constructive guidance during the study and their suggestions pertaining to preparation of this report. The same Department provided requisite laboratory and certain other facilities.

Conception and sponsorship of the investigation rests in the Maryland Department of Research and Education under its director, Dr. R. V. Truitt. The work was supported by grants from industries who use the Harbor waters. Dr. Truitt maintained the contact with and the interest of the supporters, and gave generously of his time whenever called on during the course of the investigation. He did much of the editorial work connected with the publication of this report. Baltimore City's contribution of boats and crews for the operation made possible the extensive sampling program.

Space does not permit a listing of every individual to whom thanks are due. In addition to the technical and administrative personnel contacted in private industry whose patient aid and cooperation merit recognition, material assistance was rendered by the following public agencies.

U. S. Coast and Geodetic Survey, Baltimore field office and Washington, D. C. headquarters.
U. S. Weather Bureau, Baltimore office.
U. S. Geological Survey, College Park office.
U. S. Navy
Corps of Engineers, Department of the Army, Baltimore District office.
State Department of Research and Education.
State Department of Health, Bureau of Sanitary Engineering.
State Water Pollution Control Commission.
State Department of Geology, Mines and Water Resources.
State Planning Commission.
Baltimore County Metropolitan District.
Anne Arundel County Sanitary District.
Baltimore City Health Department.
Baltimore City Bureau of Harbors.
Baltimore City Bureau of Sewers.
Baltimore City Bureau of Water Supply.

The following individuals were associated with the project for varying periods:

R. M. Clementson, *Associate Sanitary Engineer*
T. H. Garland, *Draftsman*
C. H. Hull, *Associate Sanitary Engineer*
N. E. Jackson, *Associate Sanitary Engineer*
D. W. Pohmer, *Associate Sanitary Engineer*
C. M. Weiss, *Chemist-Biologist*

Particular acknowledgment is made of special study given the subjects of photosynthetic oxygen production in the Patapsco Estuary by Mr. Hull, of industrial waste loadings by Mr. Jackson, of land-water runoff to the Harbor by Mr. Pohmer and of certain bacteriological phases of water quality in the port by Dr. Weiss.

THIS PAPER IS BASED UPON A DISSERTATION SUBMITTED TO THE ADVISORY BOARD OF THE JOHNS HOPKINS UNIVERSITY IN CONFORMITY WITH THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF ENGINEERING 1952

SYLLABUS

Baltimore Harbor is polluted by discharge of sewage and industrial wastes into tributary streams and peripheral waters. The Harbor is used extensively for navigation, industrial water supply, and recreation as well as for waste disposal. The degree of pollution varies from negligible in the principal fairway to severe in the innermost sections. Private industry discharges several hundred tons of acid materials daily and is also the principal source of organic pollution. The quality of water in Curtis Bay, Colgate Creek and the mouth of Bear Creek fails to meet desirable specifications for navigational and for pertinent industrial uses. Completion of scheduled improvements to public sewage collection and treatment facilities will soon reduce the magnitude and improve the distribution of domestic sewage loads. Pollutional effects have been intensified during the last two decades. The trend is most pronounced near waste origins, but is discernible in the fairway of the upper Harbor.

Flushing of the Patapsco Estuary is primarily effected by wind forces which are usually able to overcome the weak current system generated by river and tidal forces. Water exchange in peripheral sections is negligible except during storms. Chesapeake Bay is the major source of "new" water for the Estuary.

The Estuary has the capacity to assimilate greater loads of organic matter and acidity than are now being discharged. Degraded conditions are occasioned in limited peripheral sections by imposition of waste loads in excess of local assimilative capacities. Existing conditions can be improved by transferring pollution loads from tributary sections to the principal fairway, or by abating local waste discharges.

The public and private benefits which accrue from use of the Estuary for waste disposal aggregate many hundreds of thousands of dollars every year.

There is no indication that waste disposal as now practiced in the area has any significant effect on water quality in Chesapeake Bay.

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WATER QUALITY IN BALTIMORE HARBOR

SECTION I.

The social and economic uses of a public watercourse should be those that afford the greatest general benefit. The objective of pollution control is that of regulating waste discharges to this end. This does not mean that attempt should be made to return every natural watercourse to a state of pristine purity. Rather, it entails careful appraisal of present and probable future stream uses and decision concerning the balancing of their somewhat antagonistic water quality requirements, with due regard for the interests and good of all concerned.

The principal uses of natural salt waters are for shellfish culture, recreation and bathing, fish propagation, industrial water supply (mainly for cooling), navigation and disposal of domestic and industrial wastes. These are listed in general order of decreasing water quality requirements.

Natural abilities to accept waste discharges without production of objectionable conditions are possessed by every watercourse. It is good conservation to utilize these abilities to the maximum extent compatible with other stream uses. If this concept is accepted, knowledge of natural assimilative capacities is an essential part of a reasonable regulatory program. The principles involved are fairly well understood in the case of inland streams, but are not as clear for the tidal reaches of river mouths such as the estuary of the Patapsco River at Baltimore.

The need for a comprehensive technical investigation to provide the body of information requisite to formulation of water-quality objectives for Baltimore Harbor has become increasingly evident. Through the interest and vision of Dr. R. V. Truitt, Director of the Maryland Department of Research and Education, the Department of Sanitary Engineering and Water Resources of The Johns Hopkins University was requested in 1947 to make such a study.

PRIOR STUDIES

Several private and public agencies have concerned themselves with the water quality conditions of the Harbor. A half century ago, the Baltimore Sewerage Commission, then engaged in providing the area with its first City-wide sewerage system, reported briefly on its analysis of Harbor water.[1] Public agencies which have since investigated Harbor water quality include the Bureau of Harbors and the Bureau of Sewers of the City Department of Public Works, the City Health Department, the Bureau of Sanitary Engineering of the State Department of Health, the Chesapeake Biological Laboratory of the State Department of Research and Education, and the recently organized State Water Pollution Control Commission.

Several private organizations, such as the Gas and Electric Company and E. I. du Pont de Nemours and Company, Incorporated, analyze water from the Harbor regularly. Most of these industries use such water for cooling and are concerned with its aggressiveness.

Only limited areas have been studied previously. Many of the investigations were initiated as a result of public complaint concerning particular areas, notably Colgate Creek, Curtis Bay and vicinity, and the Sparrows Point section. The two significant exceptions to this usually very brief investigation of what were often transient conditions are the water sampling program of the City Bureau of Sewers and the investigations of the Chesapeake Biological Laboratory with reference to effects of ferrous sulfate waste discharges. The former was initiated in 1929 and entails analysis of surface water samples collected bimonthly from 13 stations within the City. The latter represents a series of studies extending over the last decade.

Most of the prior information is unpublished and is scattered in files of various public and private organizations. Available sources of information encountered during the present investigation are listed in Appendix A.

Scope of Present Investigation

The study here reported undertakes to bring into focus the fundamental technical factors requiring consideration in the matter of water quality control for that portion of the estuary of the Patapsco River comprising Baltimore Harbor. The report of findings which follows brief consideration of the complex which constitutes the Port of Baltimore is divided into sections concerned with the principal aspects of stream pollution control.

[1] 1906 Annual Report, Baltimore Sewerage Commission, p. 55 and two tables fronting.

(1) A presentation of the waste disposal problem. Pollution and stream self-purification are defined and the origins and nature of present waste loadings on the waters of the Harbor are appraised.

(2) An analysis of the hydrography of the Patapsco Estuary. Pertinent special features of land-water discharge through estuarine river reaches and their relation to waste disposal at Baltimore are considered.

(3) An evaluation of present Harbor water-quality conditions.

(4) A discussion of findings, including comment on the oxygen economy of the region, the functioning of the Estuary as a waste disposal mechanism, the present suitability of the Harbor water for uses other than waste disposal and, finally, water quality trends and future conditions.

SECTION II.

THE PORT OF BALTIMORE

GEOGRAPHY

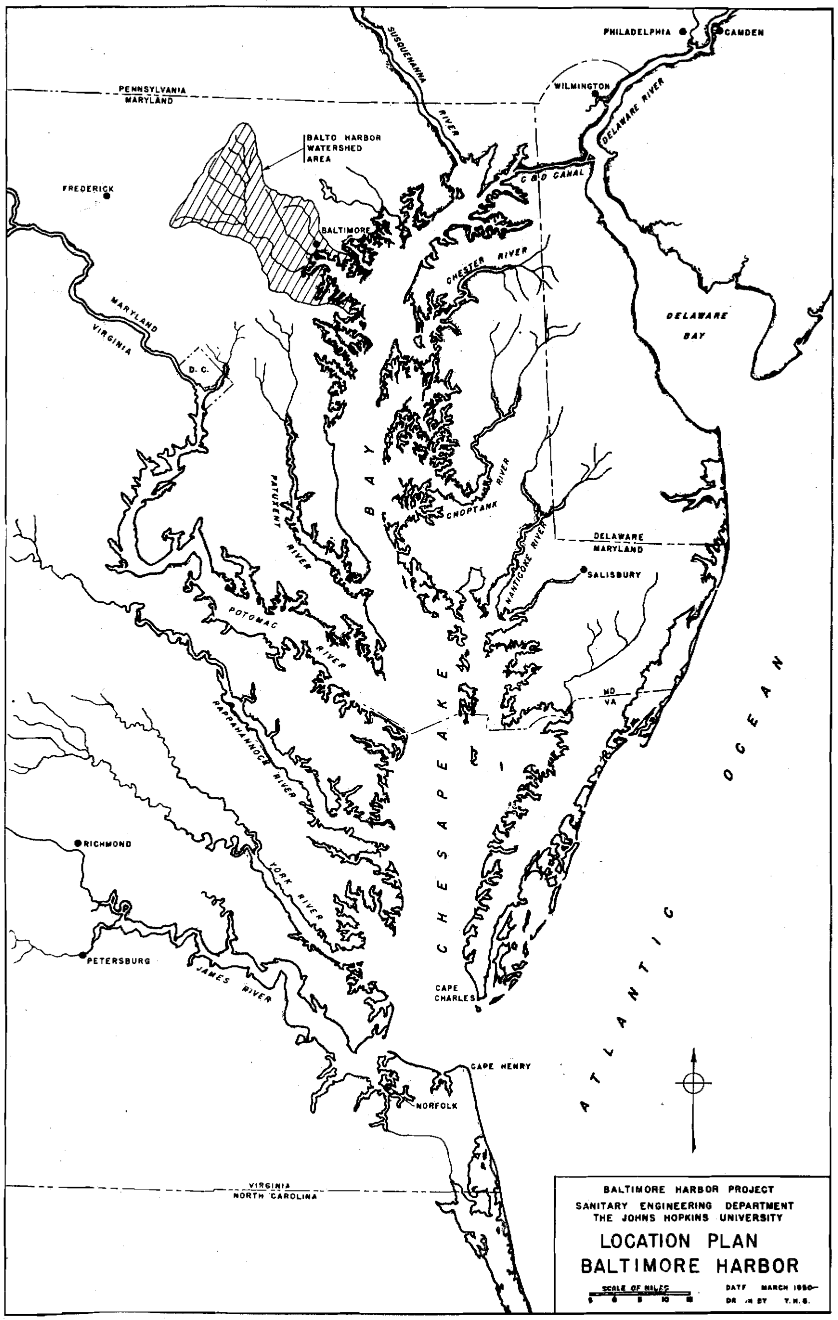
The 13-mile Patapsco Estuary comprising Baltimore Harbor is a tidal region situated on the upper west side of Chesapeake Bay about 160 miles from the Virginia capes at the entrance to the Bay (Fig. 1). The Port includes the 40 sq. mi. (square miles)* of the entire lower course of the Patapsco River inside North Point and Bodkin Point. Over half of this region is situated in Anne Arundel and Baltimore Counties outside Baltimore City, but comes within the jurisdiction of the latter for port administration. It may be divided into the Upper or Inner Harbor and the Lower Harbor. The former includes Northwest Branch and Middle Branch.** Curtis Bay and the lower Patapsco are generaly designated as the Lower Harbor.

The Patapsco Estuary receives the fresh-water runoff from 611 sq. mi. of predominantly rural watershed lying wholly within the State of Maryland. Above its tidal reach, the Patapsco River drains 60% of this total area. The only other sizable streams that enter the Harbor directly are Jones Falls and Gwynns Falls which together drain an area of 130 sq. mi. to the northwest. The former enters near the head of Northwest Branch and the latter discharges to the upper end of Middle Branch (Fig. 2). The drainage basin is largely under cultivation. Slopes to the Bay are adequate to produce rapid runoff.

TOPOGRAPHY

The Patapsco Estuary has the dendritic outline, broad surface and shallow depths which characterize the drowned streams of the Atlantic Coastal Plain. From a width of one mile off Ft. McHenry in the Inner Harbor, it broadens more or less steadily to over four miles at the Bay. Exclusive of many miles of tributary frontage above bridges, the Harbor has about 45 miles of waterfront and a total surface area of 39.3 sq. mi. The main shipway is 39 ft. deep and has a general width of 600 ft. for its 20-mile length from Ft. McHenry to the 39-ft. depth contour in the Bay. Smaller publicly

* Throughout this report, abbreviations are defined at the time of initial use.
** Strictly speaking, Middle Branch extends northwestward from Ferry Bar, but its local usage includes the water area to the west of Fort McHenry. It is so used in this report.



PHILADELPHIA
CAMDEN
PENNSYLVANIA
MARYLAND
SUSQUEHANNA RIVER
WILMINGTON
DELAWARE RIVER
BALTO HARBOR
WATERSHED
AREA
FREDERICK
C & D CANAL
BALTIMORE
CHESTER RIVER
DELAWARE
BAY
MARYLAND
VIRGINIA
D. C.
BAY
PATUXENT RIVER
CHOPTANK RIVER
DELAWARE
MARYLAND
NANTICOKE RIVER
SALISBURY
POTOMAC RIVER
MD
VA
RAPPAHANNOCK RIVER
CHESAPEAKE
OCEAN
RICHMOND
YORK RIVER
ATLANTIC
PETERSBURG
JAMES RIVER
CAPE
CHARLES
CAPE HENRY
NORFOLK
VIRGINIA
NORTH CAROLINA
BALTIMORE HARBOR PROJECT
SANITARY ENGINEERING DEPARTMENT
THE JOHNS HOPKINS UNIVERSITY
LOCATION PLAN
BALTIMORE HARBOR

Fig. 1.

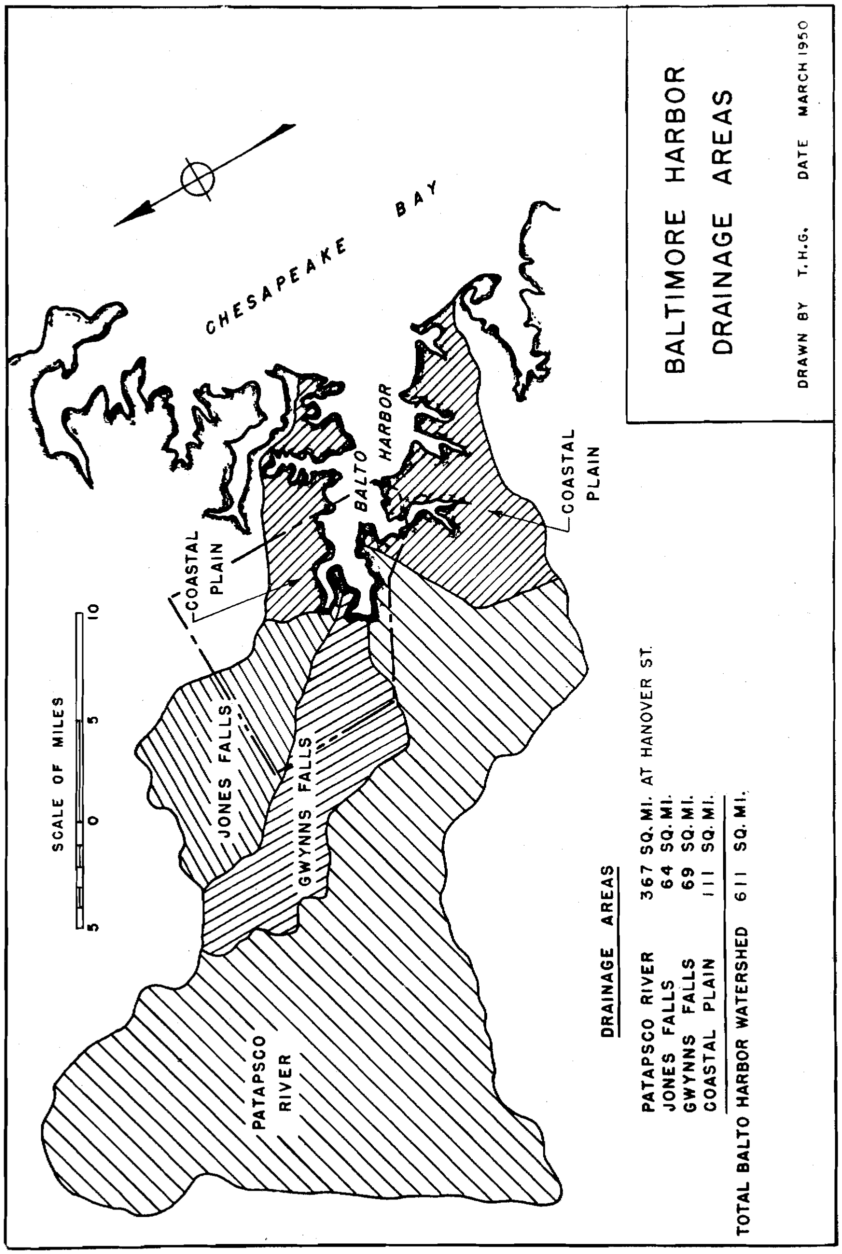

BALTIMORE HARBOR
DRAINAGE AREAS
DRAWN BY T.H.G.
DATE MARCH 1950
CHESAPEAKE BAY
BALTO HARBOR
COASTAL PLAIN
COASTAL PLAIN
JONES FALLS
GWYNNS FALLS
PATAPSCO RIVER
SCALE OF MILES
5 0 5 10
DRAINAGE AREAS
PATAPSCO RIVER 367 SQ. MI. AT HANOVER ST.
JONES FALLS 64 SQ. MI.
GWYNNS FALLS 69 SQ. MI.
COASTAL PLAIN 111 SQ. MI.
TOTAL BALTO HARBOR WATERSHED 611 SQ. MI.

Fig. 2.

TABLE 1

PHYSICAL CHARACTERISTICS OF BALTIMORE HARBOR†

Harbor Section	*Surface Area Mil. sq. ft.*	*Volumes, millions of cu. ft.*			*Average Depth, ft.***	*Exchange Ratio per cent****
		Low-tide	*Intertidal**	*High-tide*		
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Principal Fairway	721.6	10,911.3	794.9	11,706.2	15.1	14.8
Rock Creek	31.1	260.9	34.2	295.1	8.4	11.6
Stony Creek	30.9	294.0	34.0	328.0	9.5	10.4
Curtis Bay and Creek	79.2	1,121.2	87.1	1,208.3	14.2	7.2
Middle Branch	74.4	992.4	81.8	1,074.2	13.3	7.6
Northwest Branch	38.4	941.1	42.2	983.3	24.6	4.3
Colgate Creek	5.3	71.1	5.8	76.7	13.4	7.6
Bear Creek, exclusive of Humphrey Creek	66.0	627.7	72.5	699.2	9.5	10.4
Humphrey Creek	9.1		10.0			
Old Road Bay	34.1	221.3	37.5	258.8	6.5	14.5
TOTAL ESTUARY	1,090.1	15,440.0	1,200.0	16,626.8	14.2	7.2

* Assumed tidal range = 1.1 ft.
** Below Mean Low Water
*** Exchange ratio, % = 100 X local intertidal volume ÷ local high-tide volume.
† Computed from hydrographic data of U. S. Coast and Geodetic Survey Baltimore Harbor Charts 545 and 549.

maintained branch channels serve Northwest and Middle Branches and Curtis Bay, while numerous private channels lead from the fairway to shore facilities. Water depths outside of dredged channels are rarely over 18 ft.

Some of the physical characteristics of the Estuary and its tributaries are presented in Table 1. With regard to the total Harbor volume of 15.4 billions of cu. ft. below mean low water (MLW), it is notable that the proportions above the 6, 12 and 18-ft. depths amount to 38%, 75%, and 86%, respectively. The general shallowness of the region is further realized by considering the shoreline configuration which would develop if the water surface were lowered to the minus 12 and 18-ft. depths. These are shown in Fig. 3 and it is seen that at the latter depth little water surface would remain outside of dredged anchorages and channels. As a matter of fact, this area would amount to only 25% of the MLW area and a further lowering of the water surface to the minus 24-ft. depth would reduce this to twelve per cent.

Some hint of the minor influence of local tides is afforded by the data of Column (7), Table 1. The ratio of the tidal prism volume* to the volume of underlying water in a tidal region is a measure of tidal flushing potential. This ratio, called the "exchange ratio," has been computed for principal Harbor subdivisions and is very small—amounting to less than 10% on the average. The influence of tides at Baltimore is discussed in greater detail later on in this report.

CLIMATE

Baltimore is located in a region characterized by mild winters and warm summers. Seasonal changes are well marked. Severe storms are unusual and prolonged droughts infrequent.

Temperature

The proximity of large water masses (Chesapeake Bay and Atlantic Ocean) tends to stabilize temperatures at Baltimore, restricting summer and winter extremes. Table 2 summarizes temperature data for the area and shows that the mean annual temperature is 56°F. The uniform seasonal march of mean monthly temperatures is characterized by a July maximum of 78°F. and a January minimum of 35°F. Freezing weather is infrequent and

* The term "tidal prism" is applied to the volume of water between the planes of high and low water and includes the river flow into the estuary during a complete tidal cycle.

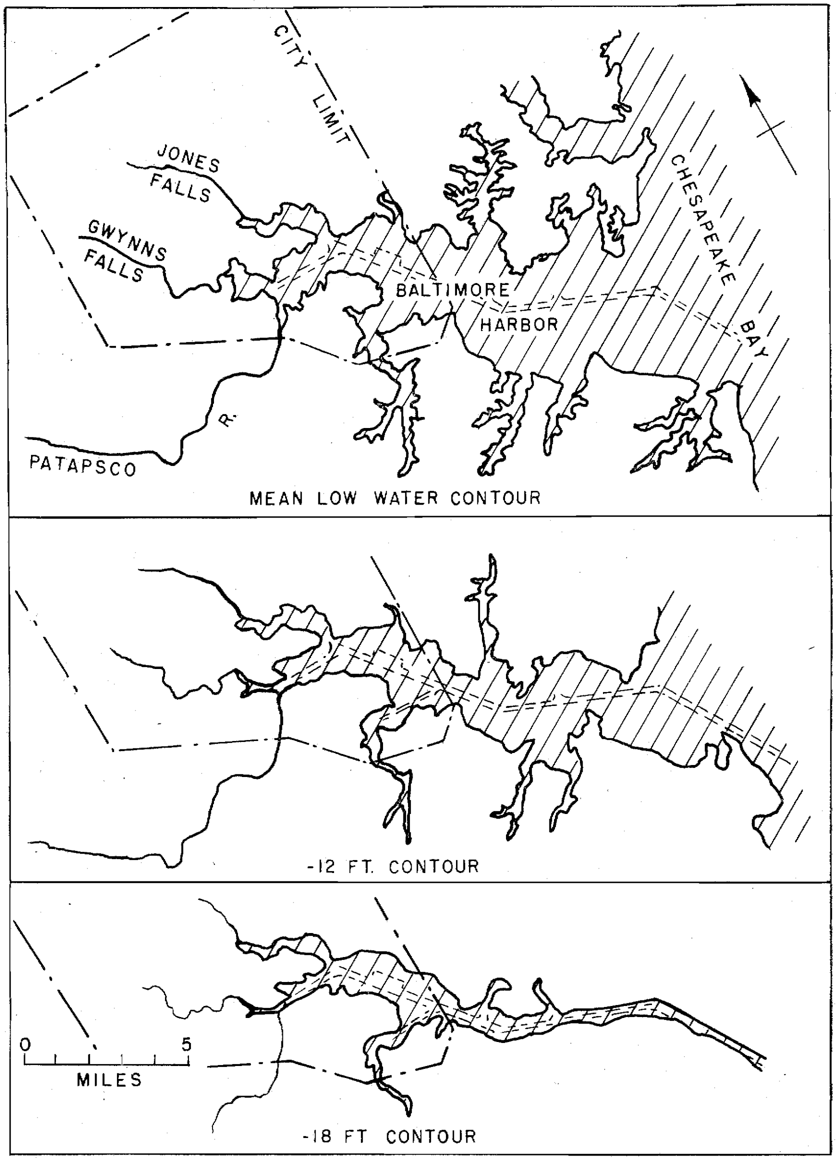


Fig. 3. BOTTOM CONTOURS, BALTIMORE HARBOR

Sketch showing general shallowness of Baltimore Harbor outside of dredged sections. Cross-hatched areas indicate water surface at Mean Low Water datum and that which would develop if water level were lowered 12 and 18 ft., respectively.

commonly of short duration. The average seasonal temperature variation of over 40°F. has a pronounced effect upon natural purification rates and other pertinent factors, as will be shown.

TABLE 2

AIR TEMPERATURES AT BALTIMORE

Month	*Mean monthly air temperature, °F.*		
	Maximum	*Average*	*Minimum*
January	47.4	34.8	24.2
February	43.4	35.6	24.3
March	54.6	43.5	35.5
April	60.4	53.6	46.4
May	70.9	64.7	59.0
June	79.8	73.3	66.7
July	81.5	77.8	71.6
August	80.4	75.6	71.0
September	77.4	69.3	63.4
October	65.1	58.2	51.5
November	54.7	47.0	41.0
December	46.0	37.5	27.4

Source: U. S. Weather Bureau records, 1871-1948.

Rainfall

Precipitation at Baltimore is abundant and uniform. Monthly information is summarized in Table 3 and indicates an annual average rainfall close to 42 in. (inches) with little monthly variation. Normal "warm season" and "cold season" precipitation averages 23 in. and 19 in., respectively. From one-third to one-half of this appears in the streams of the region, although its distribution is modified by transpiration and evaporation.

TABLE 3

RAINFALL AT BALTIMORE

Month	Total monthly rainfall, inches		
	Maximum	Average	Minimum
January	6.81	3.44	0.88
February	7.07	3.19	0.65
March	7.94	3.70	0.46
April	8.70	3.53	0.88
May	7.26	3.62	1.00
June	9.36	3.76	0.90
July	11.03	4.42	0.64
August	13.83	4.52	0.64
September	12.41	3.53	0.09
October	7.75	3.01	0.05
November	6.85	2.83	0.44
December	7.10	3.13	0.37

Source: U. S. Weather Bureau records, 1871-1948.

Sunshine

The sun shines at Baltimore during some portion of the day on about 320 days per year. Absence of cloud cover enhances the photosynthetic effect (production of oxygen by green plants normally present in natural streams) which is shown to be an important oxygen source in Baltimore Harbor.

Wind Duration and Velocity

Analysis of local winds is presented in Figure 4. Warm weather winds are about evenly distributed with regard to direction, magnitude and frequency, although a very slight prevalence of southerly winds is evident. Winds of velocity greater than 15 mph. (miles per hour) blow only four per cent of the time and nearly one-quarter of the time the weather is calm (winds 0-3 mph). Northwesterly and westerly storms result in a prevalence of winds from these directions during the cold season. The proportion of calm weather is about

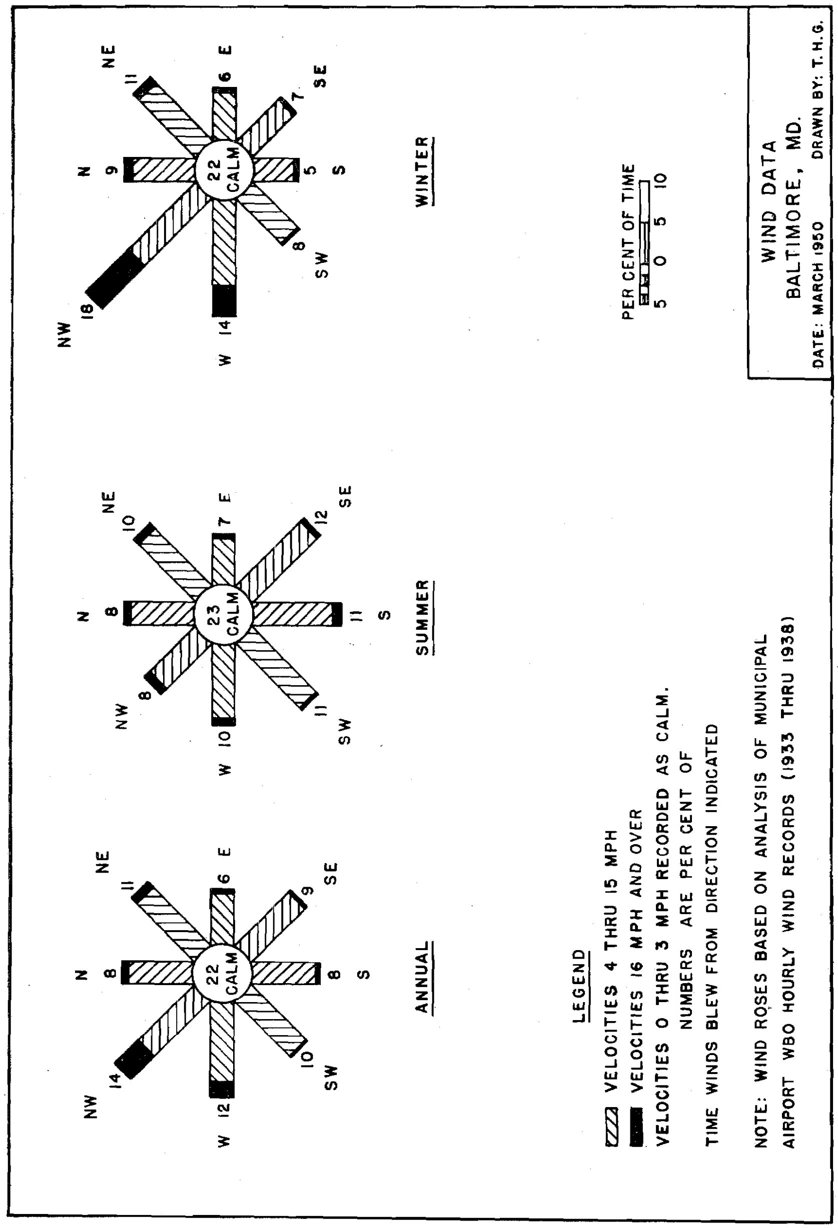

WIND DATA
BALTIMORE, MD.
DATE: MARCH 1950
DRAWN BY: T. H. G.
ANNUAL
SUMMER
WINTER
22 CALM
23 CALM
22 CALM
N
NE
E
SE
S
SW
W
NW
PER CENT OF TIME
5 0 5 10
LEGEND
VELOCITIES 4 THRU 15 MPH
VELOCITIES 16 MPH AND OVER
VELOCITIES 0 THRU 3 MPH RECORDED AS CALM.
NUMBERS ARE PER CENT OF
TIME WINDS BLEW FROM DIRECTION INDICATED
NOTE: WIND ROSES BASED ON ANALYSIS OF MUNICIPAL
AIRPORT WBO HOURLY WIND RECORDS (1933 THRU 1938)

Fig. 4.

the same for this period. Winds are shown to play a dominant role in producing water circulation and exchange within the region.

POPULATION

Baltimore, with its present population of 941,809 (1950 U. S. census), is the sixth largest city in the United States. Its remarkably stable growth in disclosed in Table 4. Residents of the metropolitan region contiguous to the Port now total approximately 1.25 millions and it is estimated that within 20 years this figure will approach 1.5 millions.

TABLE 4

POPULATION OF BALTIMORE CITY, 1850-1950

Year	*Population U. S. Census*	*Year*	*Population U. S. Census*
1850	169,054	1900	508,957
1860	212,418	1910	558,485
1870	267,354	1920	733,826
1880	332,313	1930	804,874
1890	434,439	1940	859,100
		1950	941,809

INDUSTRY

The Port of Baltimore has served international commerce for nearly 250 years and is one of the nation's principal distributing centers. A leading American industrial city, Baltimore is second only to New York in the diversity of its basic waterfront activities. Almost 100 of the nearly 2,000 industries in the area, some of them among the largest of their kind, are located along 45 miles of waterfront.

Table 5 shows that the region continues to exhibit a healthy industrial expansion. There is every reason to expect a continuation of this trend, although perhaps at a decreasing rate. The Maryland

Department of Employment and Security reports an industrial payroll for the metropolitan area aggregating close to $550 millions in 1948.*

TABLE 5

INDUSTRIAL GROWTH IN THE BALTIMORE METROPOLITAN AREA[1]
(Money figures in thousands of dollars)

	YEAR			
	1947	1939	1929	1919
Number of establishments	1,785	1,885	2,225	2,967
All employees:				
Number, Average for year	170,062	126,197	110,313	n.a.
Salary and wages, total	482,643	171,515	148,187	n.a.
Production workers:				
Number, Average for year	138,810	105,786	94,562	113,068
Wages, total	359,340	126,959	110,962	123,529
Value added by manufacture	899,534	342,465	327,520	277,655

[1] From U. S. Census of Manufactures, 1947, Vol. III, p. 37.
Baltimore Metropolitan Area includes Baltimore City, Baltimore County and Anne Arundel County.
n.a.—not available.

The value added to consumer goods during the process of their manufacture provides a satisfactory index of the relative economic importance of given industries. An analysis of local industry on this basis, Table 6, shows that the principal manufactures in order of decreasing economic importance are as follows:

a. Primary metal industries.
b. Food and kindred products.
c. Chemicals and allied products.
d. Fabricated metal products.
e. Apparel and related products.
f. Printing and publishing.
g. Machinery (except electrical).
h. Electrical machinery.
i. Stone, clay and glass products.
j. Paper and allied products.

It is worth noting that the value of goods manufactured in Baltimore City in 1947 was $660 millions.

HARBOR WATER USES

Water in the Port of Baltimore is used for navigation, disposal of domestic and industrial wastes, industrial water supply and recreation.

* As defined by the U. S. Census Bureau, the Baltimore Metropolitan Area includes Baltimore City, Baltimore County and Anne Arundel County. In general, most of the industry reported for the metropolitan area is located in or contiguous to Baltimore City.

TABLE 6

GENERAL INDUSTRIAL STATISTICS FOR THE BALTIMORE METROPOLITAN AREA, BY INDUSTRY, 1947[1]

(Money figures in thousands of dollars.)

INDUSTRY	Number of Establishments	ALL EMPLOYEES		Value Added by manufacture	Expenditures for plant and equipment
		Number, Average for year	Salaries and Wages, total		
(1)	(2)	(3)	(4)	(5)	(6)
1. Food and kindred products	332	21,169	$55,512	$144,210	$7,974
2. Textile mill products	19	2,878	6,676	12,483	1,200
3. Apparel and related products	341	16,583	38,328	76,891	1,170
4. Lumber and products, except furniture	53	1,568	4,312	5,962	660
5. Furniture and fixtures	77	2,015	4,720	7,510	173
6. Paper and allied products	39	2,847	7,081	14,723	866
7. Printing and publishing	245	8,707	26,829	49,000	1,807
8. Chemicals and allied products	136	9,477	27,292	92,644	9,641
8a. Fertilizers	14	3,127	8,309	19,865	2,092
9. Petroleum and coal products	15	2,407	(d)	(d)	(d)
10. Rubber products	7	1,260	(d)	(d)	(d)
11. Leather and leather products	19	1,282	2,934	4,894	155
12. Stone, clay and glass products	66	4,666	11,702	23,169	8,452
13. Primary metal industries	38	30,336	93,114	155,559	48,276
14. Fabricated metal products	131	16,294	43,806	78,225	6,181
15. Machinery (except electrical)	106	8,254	24,556	34,499	4,722
16. Electrical machinery	18	8,546	26,328	33,542	1,896
17. Transportation equipment	45	27,925	(d)	(d)	(d)
18. Instruments & related products	18	(d)	(d)	(d)	(d)
19. Miscellaneous manufactures	78	3,131	7,567	13,380	811
ALL INDUSTRIES, TOTAL[2]	1,785	170,062	$482,643	$899,534	$101,913

[1] From U. S. Census of Manufacturers, 1947. Data are for calendar year.
[2] Includes figures withheld to avoid disclosures.
(d) Withheld to avoid disclosing figures for individual companies.

Navigation

From an economic standpoint, navigation is the outstanding water use at Baltimore. Fortunately water-quality specifications imposed for this use are not severe or restrictive in brackish waters, to the degree which restrains other types of utilization.

Waste Disposal

Millions of gallons of domestic and industrial wastes are discharged to Baltimore Harbor daily. The economy of this practice escapes general notice. The Harbor is being used as a waste treatment unit of tremendous capacity, with consequent public and private monetary benefits which must aggregate many hundreds of thousands of dollars. These accrue as a result of elimination of the need for construction and operation of costly waste treatment works. This natural local asset has without question exerted a real, though generally unrecognized, influence upon the industrial development of the area.

Water-quality requirements as regards this category of water use are a minimum. That is to say, assignment of a higher priority to any other use at once limits the extent to which wastes may be discharged.

Industrial Water Supply

Well over one billion gallons of Harbor water are used daily by industry for cooling and cleaning. The brackish nature of the water restricts other types of industrial use. Quality specifications in this instance are intended to minimize scaling and corrosion.

Recreation

Limited boating, bathing and fishing occur within the Port of Baltimore. The City operates a public bathing beach at Fort Smallwood on Rock Point above the Harbor entrance. This location is several miles from significant pollution sources and the water here is enjoyed by many thousands of people every summer. Water conditions in the vicinity are good, thus testifying to the inherent waste-assimilative capacity of the Estuary. Private bathing is observed on a small scale in the Lower Harbor and its tributaries, but water conditions in these regions discourage such use.

It is estimated that approximately 1,000 power craft are used for pleasure boating in the Harbor area.[2] Small boat anchorages are maintained in Middle Branch, although most boat owners tie their craft up outside of the Harbor proper rather than cope with consequent maintenance problems. Fishing during some seasons of the year is good at the entrance to the Port. Fishing and crabbing within the Harbor, while practiced to a limited extent, have diminished during the last quarter of a century.

It is inevitable that the citizens of the metropolitan region should desire to avail themselves of the recreation potential of the Estuary. Twenty-five years ago, it was possible to make diverse and extensive recreational use of the Port. As time passed, however, increased navigation and waste disposal forced the citizenry largely to turn elsewhere for recreation. Fortunately, Baltimore is located in a region that abounds in nearly all recreational possibilities, thus compensating to a degree for the situation that exists, and in no small part for the industrial expansion that has taken place.

[2] Knappen, Tibbetts, Abbett Engineering Co., Report on the Port of Baltimore to Association of Commerce, Vol. II, p. 93 (1949).

SECTION III

THE WASTE DISPOSAL PROBLEM

Water plays a vital role in supporting life, in carrying forward geological processes and in cleansing the earth. As a result, during its passage over the earth's surface, it takes into solution gases and minerals, it becomes laden with suspended matter and in it grow myriads of living things. Pure water is nonexistent in nature. In the absence of man-made impurities, natural waters reach dynamic equilibrium with their environment by virtue of the interaction of a complex system of chemical, physical and biological forces. Pollution disturbs this equilibrium. Recovery of the natural balance is termed self-purification. Study of the natural equilibrium in the Harbor, of the extent to which this equilibrium is disturbed by waste discharges, and of the means by which a balance is reestablished are the fundamental objectives of this investigation.

An essential part of pollution control entails knowledge of the origin and character of wastes discharged to a given stream. From such information, a concept of probable pollutional effects is obtained. Also, it is sometimes possible to use these facts in analyzing stream assimilative capacities so as to enable prediction of the effects of modified waste discharges. In this section of the report, present waste loadings on the Patapsco Estuary are appraised.

THE MEASUREMENT OF POLLUTION

There is no universal yardstick by means of which the extent of pollution can be measured. One writer on this subject has suggested that pollution is "too much" of anything.[3]

Generally speaking, water-quality specifications for various water uses are preferential with wide tolerances. A fundamental criterion in specific instances is whether or not any of several types of bacterial, chemical or physical nuisance is created. From a practical viewpoint, a measure of judgment is involved in the determination of pollution.

When related to the various categories of water use, any of the

[3] Hedgepeth, L. L., Industrial Use of Streams, Journal American Water Works Assn., 39:532 (1947).

following several nuisance conditions developed individually or collectively in a stream as a result of waste discharge may be objectionable:

a. Presence of hazardous numbers of pathogenic bacteria.

b. Development of sgnificant concentrations of substances toxic or otherwise injurious to human, animal or plant life.

c. Existence of marked oxygen deficiencies over protracted periods.

d. Production of excessive bottom deposits of either putrescible or inert solids.

e. Formation of appreciable oily or solid scums or slicks.

f. Production of stream acidity or alkalinity beyond the normal range for the watercourse under consideration.

g. Development of perceptible color, taste or odor.

Experience has shown the value of certain chemical and physical indices of pollution. Those used in this study, together with notations as to their significance, are given in Table 7.

History of the Area

Baltimore has grown from a settlement covering about 60 acres in 1729 to one of the world's great cities. The daily activities of the 1.25 millions of residents now living in the metropolitan area, together with operation of thousands of manufacturing establishments, create a waste disposal problem of imposing proportions. As recently as 50 years ago, untreated sewage and storm water from various inadequate collection systems discharged into the numerous small streams which drain the area. As has been indicated, the two largest of these, Gwynns Falls in the west and Jones Falls in the center of the City, drain to the Inner Harbor. Summer conditions there became well-nigh intolerable due to anaerobic decomposition of settled sewage solids. Baltimore at that time was the largest American city without a comprehensive sewerage system.[4] A citizen's commission was empowered to study this situation in 1893, and to report to the Mayor and City Council. The group retained the services of two eminent consulting engineers of that day, Rudolf Hering and Samuel M. Gray, and endorsed their finding that sewage should not be discharged to the Harbor. After noting the lack of effective dilution available in the Port, the Commission reported in part:

[4] Wolman, Abel, *et al.* Report to Baltimore Commission on City Plan, Present and Proposed Physical Facilities, p. 22, (1942).

TABLE 7—*Continued*

Test	*Remarks*
8. Dissolved Oxygen (D.O.)	Measures the quantity of dissolved oxygen in a water sample. Oxygen is essential for maintenance of normal stream flora and fauna. Aerobic stabilization of pollutants is desirable to avoid production of the odorous and toxic end products of anaerobic decomposition. Saturation values are upper limits for solution of atmospheric oxygen and are reduced by increasing temperature and salinity. Mean saturation values for the Harbor are 13 ppm. in winter and 8 ppm. in summer. Supersaturation may result from oxygen produced by green plants present normally (photosynthesis). Saturation deficits in natural waters indicate that oxygen resources are being drawn upon to satisfy requirements of chemical and biochemical stabilization of substances present in these waters; the magnitude of such deficits is an index of the sanitary status of surface streams.
9. Conductivity	An electrical measurement from which the concentration of dissolved salts in aqueous solution can be determined. Used in this investigation to study brackish-water distributions.
10. Ether-soluble material	Measures the content of grease, fat and oil in a sample. Used on bottom muds in this study to ascertain areas subject to more or less frequent oil pollution.
11. Total and volatile solids content of muds	Indicates physical state of deposited material and approximate amount of contained organic matter. Provides insight into benthal oxygen requirements and character of accumulated sediments.
	BACTERIOLOGICAL TESTS
12. Most probable number (M.P.N.) of coliform bacteria	An index of human and animal sewage pollution. The standard determination is based upon the theory of probability and yields the number of bacteria most likely present in the sample at the time of testing. This group of bacteria is present normally in human and animal feces in very large numbers; it may also be present in very small numbers in soils .Its gross presence—usually not dangerous in itself—constitutes a health hazard since fecal pollution indicates the probable presence of pathogenic bacteria.

TABLE 7

SIGNIFICANCE OF WATER AND MUD ANALYSES USED IN BALTIMORE HARBOR STUDY

	Test	*Remarks*
		PHYSICAL-CHEMICAL TESTS
1.	Temperature	Controls solution of atmospheric oxygen and hence its saturation value. Influences natural purification rates (they increase with temperature).
2.	Chlorides	Indicate the approximate concentration of sea water in brackish-water dilutions.
3.	Alkalinity	Measures the total quantity of alkali or alkaline salts present. Determined by titration with a solution of a strong acid to certain standard hydrogen-ion equivalence points and hence is a measure of buffer capacity.
4.	Acidity	Measures the total quantity of acid or acid salts present. Determined by titration with a solution of a strong base to certain standard hydrogen-ion equivalence points. Indicates capacity for reaction with alkalinity.
5.	pH	Expresses the intensity of the quantity factors acidity and alkalinity. Commonly varies from about 6.7 to 8.6 in unpolluted estuaries. Reflects equilibria among certain dissolved substances present naturally in surface waters, largely carbon dioxide components. Excessive variation in pH usually indicates artificial pollution with strongly acidic or alkaline soluble substances.
6.	Iron	Aids appraisal of the fate of certain iron-bearing wastes in Baltimore Harbor.
7.	Biochemical Oxygen Demand (B.O.D.)	Measures the amount of oxygen required for biochemical stabilization of organic (decomposable) material. A time-temperature function, it is usually determined by incubating samples at 20°C. for five days. Estimation of B.O.D. for other conditions of time and temperature possible after detailed study of oxygen-demand characteristics of waste or stream samples.

> "... whatever solid matter is permitted to enter the harbor remains there, sinking to the bottom or floating on the surace as the case may be but never getting far away from the point of entrance; so that sewage and other filth, if allowed to enter with storm water, are not in this way gotten rid of, but continue a source of nuisance and, after befouling the harbor and silting up the channels, the accumulating matter has to be removed in the end by dredging."[5]

As a result of the report of this initial group, another commission was authorized by the State Legislature in 1904 and established during the following year. Construction of comprehensive separate systems for the collection and disposal of sanitary sewage and storm water began in 1906. The systems built then at a cost of more than $20 millions have been extended and improved until today the City proper is served by over 1,600 miles of sewers and drains which with appurtenant treatment works are valued at over $100 millions.[6]

Waste Loadings on the Patapsco Estuary

In the paragraphs which follow, an attempt is made to evaluate quantitatively the origin, amount and character of wastes which are discharged to the Patapsco Estuary.

The several types of waste loadings on the Harbor may be classified in three broad groups.

a. Pollution contributed by tributary streams.

b. Domestic sewage discharges.

c. Industrial waste contributions.

Tributary Streams

Water reaching the Harbor through tributary streams contains a quantity of "natural" and man-made or artificial pollution. The character of natural pollution has been noted heretofore as consisting chiefly of soil leaching and erosion products which are picked up by surface water as it runs overland to the sea. While the concentration of such material is doubtless augmented by human activity such as farming, cattle raising and road and home construction it is customary to regard this content of surface waters as being outside the usual definition of the term "pollution." Thus, a distinction is made between natural and artificial pollution. However, a portion of the natural pollutional content of surface streams is putrescible and must be included, therefore, in any complete discussion of waste loadings.

[5] 1897 Report of the Sewerage Commission of the City of Baltimore, pp. 12-13.
[6] 1949 Annual Report, Baltimore Department of Public Works, p. 272.

No attempt was made in this study to appraise specific sources of pollution above the Estuary. The aggregate effect of such waste loadings, both natural and artificial, was evaluated from estimates of B.O.D. and main stream discharge. B.O.D. from this source appears to have averaged approximately 8,000 lbs. per day during the warm seasons covered by this study. (Cf. Table 8).*

Domestic Sewage

Most of the domestic waste originating in and around Baltimore does not reach the Harbor directly. The City's principal sewage treatment works is situated to the east on Back River off the Harbor watershed. The Back River works provide for complete treatment of sewage in terms of screening and grit removal, primary and secondary sedimentation, trickling filtration and activated sludge treatment, separate sludge digestion and chlorination. Facilities are presently under construction for the drying of digested sludge by heat. The plant capacity approaches 175 mgd. and current flows (April, 1951) are in the neighborhood of 130 mgd.

The total population connected to these works as of December, 1949, was estimated[7] to be 976,000. This is more than the City population because appreciable areas in Baltimore County are connected to this system. About two-thirds of the total flow reaches the works by gravity. The remainder discharges to a large pumping station at the western terminus of Eastern Avenue on the Northwest Branch of the Harbor whence it is lifted into the main outfall sewer to Back River. The pumping station is provided with an emergency overflow to the Port, but installed pumping capacity is such that it is rarely necessary to by-pass sewage in this manner.

The Patapsco Treatment Works on Wagners Point north of Curtis Bay serves South Baltimore and its environs. This plant affords primary treatment, including screening, grit removal, sedimentation and separate sludge digestion. Treated effluent is discharged to the Harbor off Wagners Point through a submerged outfall. A capacity of at least 5 mgd. is available here. The 1949 flow averaged 1.36 mgd.from an estimated connected population of 23,100.[8]

The status of public sewerage in the City proper during this investigation is depicted in Fig 5. Significant Harbor natural and artificial pollution, exclusive of industrial wastes, is noted in Table 8.

* Unless stated otherwise, the term B.O.D. as used in this report refers to 5-day, 20°C. values.
[7] 1949 Annual Report, Baltimore Department of Public Works, p. 262
[8] 1949 Annual Report, Baltimore Department of Public Works, p. 267.

TABLE 8

BALTIMORE HARBOR: PRINCIPAL SOURCES OF BIOCHEMICAL OXYGEN DEMAND[1]

Sources	*5-Day, 20°C. B.O.D. lb. per day*	*Equivalent Population*
I. ANTECEDENT NATURAL AND ARTIFICIAL POLLUTION REACHING HARBOR THROUGH STREAMS		
A. Gwynns Falls (10 ppm. x 47 cfs. x 5.4)[2]	2,540	15,000
B. Jones Falls (7 ppm. x 44 cfs. x 5.4)[2]	1,660	9,800
C. Patapsco River at Relay (U. S. Route 1) (3 ppm. x 250 cfs. x 5.4)[2]	4,050	23,800
II. DOMESTIC SEWAGE		
A. *Curtis Bay*		
1. Anne Arundel County Sanitary District primary sewage treatment works (primary sedimentation and chlorination) for Glen Burnie-Harundale-Glen Gardens section. Effluent to Furnace Creek. One-third treatment credit for connected population of 10,000[3]	1,140	6,700
B. *Patapsco River below Relay*		
1. Raw sewage from South Baltimore (Brooklyn Park in Anne Arundel County and portions of Brooklyn in City) discharged through Chesapeake Avenue sewer off Potee Street[3]	1,020	6,000
2. Raw sewage from Linthicum-North Linthicum outfall sewer (Anne Arundel County Sanitary District) at Old Annapolis Road (U. S. Route 301)[3]	610	3,600
3. Raw sewage from Catonsville-Halethorpe-Arbutus (Baltimore County Metropolitan District) Herbert Run outfall sewer about 5 miles above the Hanover Street bridge[3]	3,400	20,000

TABLE 8—*Continued*

BALTIMORE HARBOR: PRINCIPAL SOURCES OF BIOCHEMICAL OXYGEN DEMAND[1]

Sources	*5-Day, 20°C. B.O.D. lb. per day*	*Equivalent Population*
4. Baltimore City's Reedbird Sewage Treatment Works (primary sedimentation) serving Cherry Hill section just west of Hanover Street. One-third treatment credit for flow of 0.3 mgd. at 50 gallons per capita per day[3]	680	4,000
C. *Main Harbor*		
1. Raw sewage from approximately 350 acres of heavily populated Baltimore City area in Highlandtown on Eastern Avenue. Assumed population density: 95 persons per acre. Discharges on north side of Harbor east of Lazaretto Point[3]	5,610	33,000
2. Baltimore City's Patapsco Sewage Treatment Works (primary sedimentation) serving South Baltimore. Effluent off Wagners Point[4]	3,380	20,000
3. Sparrows Point Sewage Treatment Works (primary sedimentation and chlorination) serving community of Sparrows Point. One-third treatment credit for estimated connected population of 7,500[3]	850	5,000
GRAND TOTALS	24,940	146,900

[1] As of December 31, 1950. Exclusive of sanitary and industrial wastes from manufacturing establishments in unsewered areas. Also, not including miscellaneous septic tank and other discharges whose aggregate influence is negligible.
[2] From best estimates of B.O.D. and mean stream discharge. Equivalent population based on 0.17 pounds of B.O.D. per capita per day.
[3] From estimated connected population and daily per capita B.O.D. of 0.17 pounds.
[4] From mean flow of 1.4 mgd., effluent B.O.D. of 290 ppm.

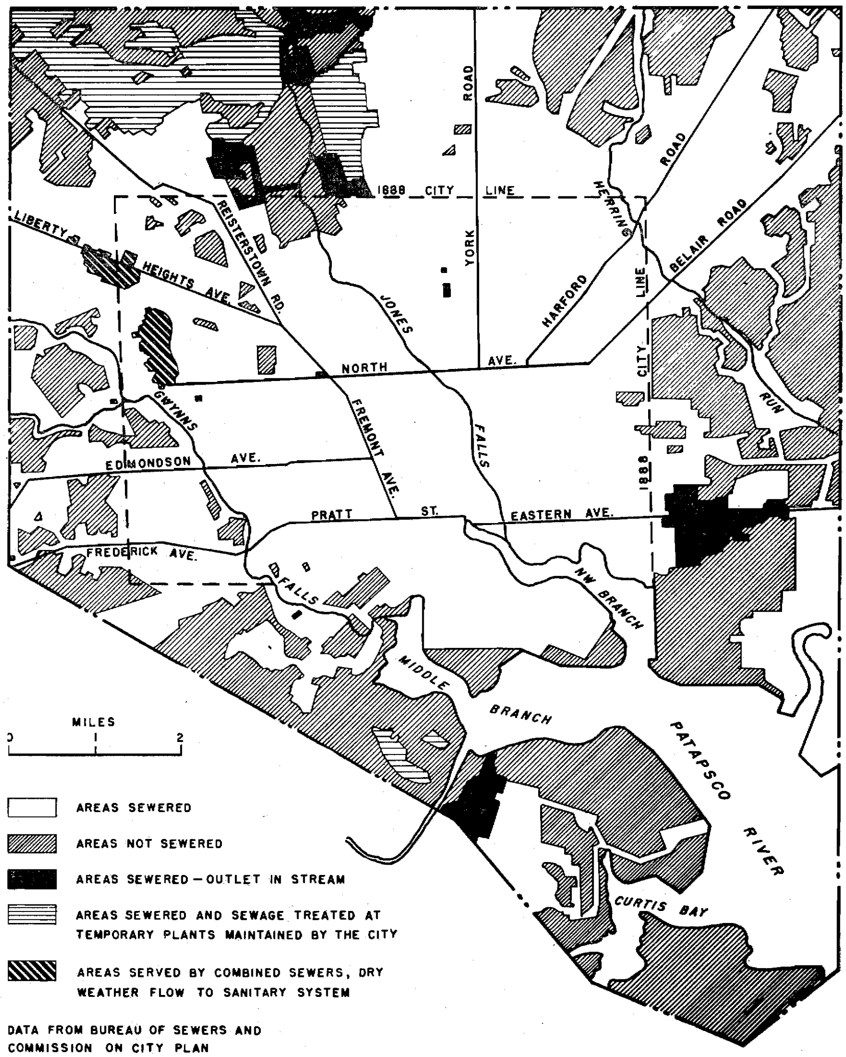


Fig. 5.

STATUS OF PUBLIC SEWERAGE

Baltimore City, December, 1950

Since the oxygen demand of this waste category constitutes one of its principal liabilities, loadings are expressed as B.O.D. and equivalent population. The concept of population equivalence is useful to establish a common denominator for certain types of waste discharges. Studies have shown that in the United States the average daily per capita discharge of 5-day, 20°C. B.O.D. approaches 0.17 lb. From this figure, it is possible to convert quantities of B.O.D. to equivalent population and vice versa.

Wastes from manufacturing establishments located in unsewered areas are not included in these data. Rather they are discussed separately. It should be noted here that the information in Table 8 represents waste loadings as they existed during the period of this study. They do not reflect recent improvements effected as part of the long-range sewerage program for the metropolitan area. This base was adopted to make these data comparable to the water-quality information of this investigation.

During the summer of 1951, raw sewage discharges from Baltimore City's Chesapeake Avenue sewer and the Baltimore County Metropolitan District's Herbert Run outfall were connected through two lift stations to the Patapsco Sewage Treatment Works on Wagners Point. It is intended that the Linthicum sewer in Anne Arundel County will be tied into this same sytem. In addition, completion of an interceptor along Jones Falls and extension of this facility north into Baltimore County as planned will eliminate significant pollution of that stream. Sewage collected in this manner will be conveyed to the Back River Works for treatment. Cleanup of the Eastern Avenue raw sewage area awaits appropriation of funds; these wastes will also be diverted to the Back River plant.

Completion of the program noted above should reduce the daily sewage B.O.D. load imposed on the Harbor water during this study by close to 9,000 lbs. This figure comprises the 5-day oxygen demand of sewage to be taken to the Back River Works from Highlandtown and the Jones Falls drainage basin, together with a credit of 2,000 lbs. per day for primary treatment of sewage discharges transferred to the Patapsco Works. Thus, the oxygen requirements of this category of Harbor pollution will soon be reduced to perhaps 9,000 lbs. per day as 5-day B.O.D., or about one-half the loading which obtained during the present investigation.

Of greater significance is the fact that appreciable waste loadings are being removed from tributary streams and peripheral Harbor waters of limited assimilative capacity to a section of the Estuary off Wagners Point where conditions are more favorable for disposal.

It is probable that flows to the Patapsco Sewage Treatment Works on Wagners Point will increase by 7 or 8 mgd. during the next decade or two. Of this total, it is estimated that flows from Baltimore County, the City proper and Anne Arundel County will be 4, 3 and 0.5 mgd., respectively. The rated capacity of the present plant is about 5 mgd., although certain existing treatment units are designed to handle up to 15 mgd.; so additional facilities will have to be provided. Both the added capacity and secondary treatment have been recommended for construction prior to 1960 by the City's consulting engineers.[9]

Turning again to conditions extant during the period of the present study, it is evident from Table 9 that 70% of the domestic sewage load imposed on the Estuary was discharged through the Inner Harbor.

Industrial Wastes

Baltimore is essentially a manufacturing city. Of the total individual concerns reporting under unemployment compensation and employing 100 or more persons, 57% are engaged in manufacturing. According to a recent study, about two-thirds of the total City employment are concerned with the manufacture and the movement of consumer goods.[10]

Many of the nearly 2,000 plants in the area are connected to public sewers. However, a part of them are on the waterfront and discharge waste materials directly to the Harbor. Others are many blocks off the water, but are connected to it through storm sewers. Since detailed analysis of every industrial establishment discharging wastes to the Port was impracticable, effort was centered on plants known to be in unsewered areas and which, because of the nature of their operations, would be most likely to produce water-carried wastes.

The region under consideration is one of the world's leading producers of commercial fertilizers and some of its other industries are among the largest of their kind. Information was obtained from 72 establishments, covering production of many types of or-

[9] Wolman, Abel, *et al.*, Report to Baltimore Commission on City Plan, Present and Proposed Physical Facilities, p. 28, (1942).
[10] Baltimore: Some Economic Indicators, Studies in Business and Economics, Vol. 2, No. 4, Bureau of Business and Economic Research, College of Business and Public Administration, University of Maryland, (March, 1949).

ganic and inorganic chemicals, iron and steel and their products, sand and gravel, electric power and equipment, and canned foods. A detailed discussion is found in Appendix B concerning waste sampling and gaging procedures utilized in this work. Table 9 presents information for plants surveyed. Difficulties in measuring flows and interpreting quality tests are increased in some industries by the discharge of large volumes of brackish cooling water to sewers carrying process wastes. For instance data on discharges from the steel mill on Sparrows Point have not been included partly because the effect of cooling water circulation could not be evaluated.

It is difficult to arrive at reasonable figures for waste loadings around Sparrows Point. The steel mill covers many square miles and includes dozens of operations. Wastes are discharged to the Harbor and its tributaries through 28 individual outlets, several of which enter Humphrey Creek. While the latter was once entirely open to Bear Creek, it has now been partially isolated by construction of a sheet-pile dam across its entrance. The top of this barrier is about at mean low water and the Creek is subject to tidal influences at least in part. Some neutralization, precipitation and coagulation doubtless occur here. These actions, together with whatever subsidence is effected behind the barrier, modify effluents from sewers discharging therein to an extent as yet unknown. Complete evaluation of waste loadings from this mill requires much more intensive study than could be brought to bear during this investigation by project and mill personnel.

Even though the data of Table 9 are incomplete, it is entirely clear that the Harbor waters receive tremendous quantities of wastes by direct discharge from industrial establishments. Most of the data on wastes included in the table were produced during the course of various metallurgic or chemical manufacturing operations. These wastes were dilute solutions of substances whose recovery was deemed uneconomical.

The B.O.D. loading from the industries surveyed, including employee sanitary waste, totals more than that from all other waste categories combined. Manufacturers of petroleum products; coke, gas and allied byproducts; and baker's yeast were the principal sources of this type of oxygen demand.

Industries which contributed the greatest quantities of total solids included producers of pigment, iron and steel products and superphosphate fertilizers. The hydrolysis and oxidation products

TABLE 9

INDUSTRIAL WASTES DISCHARGED TO BALTIMORE HARBOR

(Data for 72 plants surveyed during period June-October, 1950)

ITEM	*Northwest Branch*	*Middle Branch*	*Colgate Creek*	*Curtis Bay-Fairfield*	*Bear Creek* and vicinity*	*Totals*
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Number of plants visited	10	10	5	45	2	72
Number of plants discharging wastes	6	5	5	15	2	33
Harbor water for cooling, average mgd.	85	182	10	40	690	1,007
Waste volume, mgd.	6.9	2.8	4.1	7.9	2.6	24.3
5-day, 20°C., B.O.D., tons per day	7.7	0.1	4.2	1.9	0.5	14.5
Suspended solids, tons per day	17.2	9.7	5.9	86.6	....	119.6
Fixed solids, tons per day	26.8	4.7	35.2	285.6	116	468.3
Total solids, tons per day	31.4	11.8	48.3	476.7	149.4	717.6
Ether-soluble material, tons per day	10.6	0.4	2.4	0.1	....	13.4
Acidity (as $CaCO_3$), tons per day	23.0	0.0	25.1	155.1	25	228.1
Alkalinity (as $CaCO_3$), tons per day	5.4	0.2	0.2	0.2	....	6.0

* Exclusive of uncertain quantities from Bethlehem Steel Company's Sparrows Point plant.

resulting from discharges of waste copperas ($FeSO_4.7H_2O$) from pigment and metal pickling operations contribute heavily to the suspended solids content of the waters of the Estuary. Oil refineries were primary sources of ether-soluble substances such as fats, oils and greases. All of the significant acidity discharged as such or generated by hydrolysis of acid salts after their dilution in the Harbor waters was occasioned by wastes from metal pickling operations, from the manufacture of paint pigment and from superphosphate fertilizer plants. Oil refineries were the only source of appreciable quantities of alkaline wastes.

Oil discharges from both navigational and shore facilities, sometimes willful and sometimes accidental, have long been sources of vexation to City and Federal authorities. Pollution of this nature became aggravated during and after World War II. The City Bureau of Harbors has operated an oil-recovery barge since 1946 and has waged an intensive oil-control campaign during recent years. As a consequence of education and more stringent law enforcement, slop-oil recovery dropped to less than 500 gallons in 1949 from about 34,000 during the previous year.

The scavenging of hazardous and unsightly floating timber and trash is effected by the City Bureau of Harbors and the Army Engineers, the former in and around docks and slips and the latter in fairways. About 8,000 cu. yds. of such material were removed in 1949.

Summary

This section of the report in which the origin, amount and character of wastes discharged to Baltimore Harbor are appraised, may be summarized as follows:

a. The distribution of known B.O.D. loading by waste category is shown below.

Source	*5-day, 20°C. B.O.D., lb. per day*	*Population equivalent**	*Per cent of total*
1. Antecedent natural and artificial pollution reaching the Patapsco Estuary through tributary streams	8,200	50,000	15
2. Raw and treated domestic sewage	16,700	100,000	30
3. Manufacturing wastes and industrial sanitary sewage	31,000	180,000	55
Totals	55,900	330,000	100

* 5-day, 20°C. B.O.D. basis. Rounded figures.

The foregoing data for tributary streams and domestic sewage are regarded as sound estimates. Actual industrial-waste B.O.D. is doubtless greater than the amount noted, since not all sources were studied in the field. The figure of 31,000 lb. of 5-day B.O.D. per day is conservative.

b. Approximately one-half of the B.O.D. loading from all waste sources reached the Estuary via the Inner Harbor. As a matter of fact, sewage discharges from the Highlandtown section and from the Patapsco Sewage Treatment Works might will be considered as Inner Harbor loadings. When these are included, the proportion of the load upon the Inner Harbor approaches seventy per cent.

c. Sewer system changes to be completed in the near future will probably reduce by one-half the oxygen requirements imposed by domestic sewage discharges during the investigation. The remaining 5-day B.O.D. load of about 9,000 lb. per day may be expected to approach 14,000 lb. by 1970, assuming normal development of the area and primary treatment of sewage conveyed to the Patapsco Works. This is approximately equivalent to the sewage load which obtained during this study. However, the more favorable treated sewage discharge location should improve conditions in peripheral Harbor waters of limited assimilative ability. The present rated capacity of Baltimore City's Patapsco Sewage Treatment Works will need to be increased shortly to permit treatment of agumented sewage flows.

d. Industrial waste discharges to the Harbor are predominantly acidic. Alkaline trade wastes are few. Thus, reaction with natural stream alkalinity affords the only significant neutralization of acidic wastes.

e. Superphosphate fertilizer, pigment and steel products plants are the principal sources of several hundred tons of acidity and solids discharged to or precipitated within the Estuary each day. Waste copperas in acid solution from the steel mill and pigment plants contribute heavily to the aggregate acidity and solids loads.

f. Control of floating oil, trash and debris in Baltimore Harbor requires the constant vigilance of municipal and federal agencies.

SECTION IV.

HYDROGRAPHY OF THE REGION

It has been noted heretofore that a second principal phase of stream sanitation involves hydrographic study of the stream. This section of the report presents findings regarding water movement within and through the Patapsco Estuary.

Answers to certain fundamental questions are needed.

a. What dilution is available for waste discharges at a given location?

b. What dispersion patterns may be expected to develop for specific waste discharges?

c. How much time must elapse before specific water masses and their contained pollution are discharged finally from the area?

GENERAL CONSIDERATIONS

An estuary is a region where fresh and saline waters are mixed. In the absence of complicating circumstances, therefore, study of brackish-water distributions provides a means of appraising the magnitudes of mixing (dilution) and flushing which result from interaction of local river runoff, winds and tides. Present knowledge concerning shallow tidal waters is such that it is impossible to determine quantitatively how these factors combine to produce observed distributions.[11]

Observed Salinity Distributions

Field studies of the estuarine reaches of simple streams discharging to the ocean along the Atlantic coastal region of the United States have demonstrated certain characteristic salinity distributions. Stripped of complications, a positive seaward gradient exists and bottom water at any location is more saline than surface water. Interpretation of these distributions from any of several viewpoints leads to the conclusion that what is in reality a complex exchange of fresh and salt waters may be resolved into two net flows involving a seaward discharge of fresh water and a variable sea-water intrusion along the bottom (because of its greater density) from which upward discharge of salt water occurs in amounts sufficient to produce the observed longitudinal gradient and to preserve the salt balance

[11] Ketchum, Bostwick H., Hydrographic Factors Involved in the Dispersion of Pollutants introduced into Tidal Waters, Jour., Boston Society of Civil Engineers, 37:296 (1950).

of the region. A quantity of fresh water equivalent to river flow during a complete tidal cycle must discharge to the ocean during each cycle, else the fresh-water volume within the estuary would increase. Furthermore, the progressive mixing of salt water with this net seaward flow increases the volume that must move downstream as the fresh water passes through the estuary. Tidal action causes the system described to oscillate within the brackish reach.[12]

The increased downstream flow explains in part the observed enhancement of dilution as wastes are transported down the estuary. A further significant result of the system is that pollutants reaching the bottom are carried by the underflow up the estuary to the limit of salt water penetration.

Flushing Time

The mean time for a particle of fresh water to pass through the brackish reach is termed the flushing time of an estuary and is equal to the fresh-water accumulation within the region divided by the river flow. The fresh water present momentarily at any location is a complex mixture of river water accumulated during a number of previous tidal cycles. Two techniques are available for ascertaining its aggregate volume. It may be calculated from the salinity data of field surveys or it may be estimated by application of an empirical method developed recently at the Woods Hole Oceanographic Institution.[13] The latter technique becomes cumbersome for conditions other than the steady state (constant river flow and tidal range) and attempts to determine a general differential solution for the transient conditions which actually obtain have so far proved unsuccessful.

Wind Effects

Where conditions are favorable, local winds and weather may play an important role in producing estuarine currents. Upper water layers are forced downwind and consistent movement of surface water in one direction generates subsurface counterflow. The depth and magnitude of such wind stirring depend upon the velocity and duration of winds from a given direction and upon the fetch, the vertical density gradients and the local topography.

[12] Survey of the River Tees, Part I—Hydrographical, Tech. Paper No. 2, British Water Pollution Research Board (1931), pp. 10-13.
[13] Ketchum, Bostwick H., The Exchanges of Fresh and Salt Waters in Tidal Estuaries, Proceedings of the Colloquim on the Flushing of Estuaries, Woods Hole Oceanographic Institution (1950), p. 1.

Physical Features

The topography of the Patapsco Estuary has been considered in Section II of this report. It will be recalled that the mean depth of the Estuary is only 15 ft. and that peripheral sections are even shallower. The rapid downstream enlargement of the Patapsco is accompanied by a reduction in average depth. Furthermore, at its entrance the River is effectively "pinched off" by transverse bars extending toward the channel from North Point on the north and Rock Point on the south. These barriers tend to force bottom water to enter and leave the region via the main channel.

Another significant constriction of the Port exists in the vicinity of Ft. Carroll between Sollers Point on the north side and Hawkins Point on the south. The projection of Sollers Point Shoal virtually reduces the effective section at this location to the main channel.

Upland Drainage

Since discharge records for smaller tributary streams are incomplete, it has been necessary to estimate the total freshwater runoff to the Port from upstream records for the Patapsco. Discharge measurements for the North Branch of the river at Marriottsville (1929 to date; drainage area 165 sq. mi.) accord with the more complete records for the Gunpowder River and other Piedmont streams.[14] Accordingly, unit discharges for Marriottsville have been applied to the entire watershed to obtain the monthly variation indicated in Fig. 6.

Temperature and river discharge effects on quality are critical during the warm summer months. Attention will be limited, therefore, at this point to the summer period. Assuming the runoff from the total Harbor watershed enters the head of the Port and making no allowances for present or future water diversions, analysis of discharge records for summer months during the period 1929-47 yields the data of Table 10.* Average summer land-water flow to the Port totals only 416 cfs. (268 mgd.) and even lower flows may be expected with frequencies show in the table. As stated above, water diversions have not been deducted from estimated runoff, so that figures presented here are high. It is shown that even these generously estimated flows exert negligible influence upon

[14] Pohmer, David W., A Study of Certain Agents Influencing the Hydrology of Baltimore Harbor, Master's Thesis, The Johns Hopkins University (1948), pp. 4-14.

* The frequency of summer flows closely approximates a straight line on log probability paper with geometric mean = 0.68 cfs. per sq. mi. and geometric standard deviation = 1.71 cfs. per sq. mi.

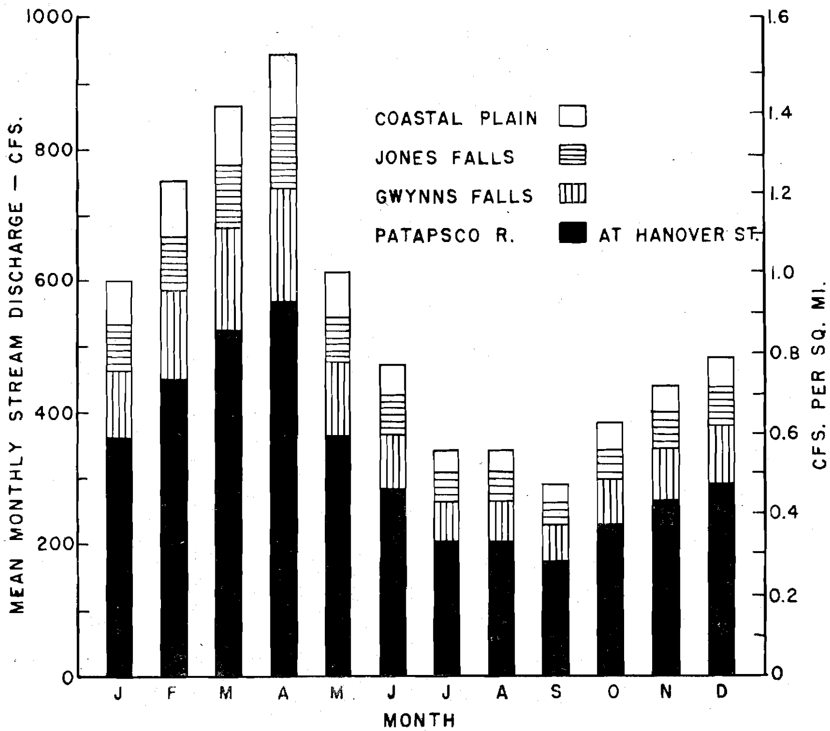


FIG. 6.

MEAN MONTHLY UPLAND DRAINAGE TO BALTIMORE HARBOR

(From application of monthly U.S.G.S. stream-flow records for North Branch of Patapsco River at Marriottsville to total Harbor watershed. No diversions included.)

TABLE 10

PATAPSCO RIVER, PROBABLE SUMMER RUNOFF

Recurrence Interval, yrs.	*Per cent Chance Rate*	*Expected Runoff**		
		Unit	*Total***	
		Cfs./sq. mi.	*Cfs.*	*Mgd.*
(1)	(2)	(3)	(4)	(5)
2	50	0.68	416	268
5	20	0.44	269	174
20	5	0.28	171	110
50	2	0.23	141	91
100	1	0.20	122	79

* In terms of potential stream discharge as low or lower than the stated value.
** Based on a total drainage area of 611 sq. mi. at Bodkin Point.

flushing of the Estuary, so further refinement of the analysis is unwarranted.

The magnitude of currents which might result from river flow in the absence of wind and tidal effects is negligible. The effective area of a transverse Harbor section through Ft. Carroll is approximately 60,000 sq. ft. River discharge approaching an average of 1,000 cfs. occurs during April, the maximum month. Such a flow would produce a current of less than 0.02 fps. or 1.2 feet per minute through this relatively restricted section.

Baltimore City is going to the North Branch of the Patapsco for an additional source of water supply. Construction of a 43-billion gallon storage reservoir on the stream at Falls Run a few miles above the confluence of the North and South Branches is expected to supply up to 94 mgd. Although completion of this development will reduce the volume of fresh water reaching the Harbor, its effect will be unimportant.

Tides

Tides and currents in the Chesapeake Bay and its tributaries pose no serious navigational or channel maintenance problems and have not been studied extensively. The U. S. Coast and Geodetic Survey has reviewed pertinent information accumulated during the period 1845-1930.[15]

Tidal movement in Chesapeake Bay is a continuation of the Atlantic Ocean tidal wave which enters through the Virginia capes and is propagated up the Bay and its tributaries. Mean tidal ranges for the region decrease from slightly less than three feet at the capes to under one foot just south of the Patapsco, then increase to about two feet at Aberdeen. Maximum currents at the entrance are only 1 to 1.5 knots for flood tides and 1 to 2 knots for ebb.* From mouth to head, maximum velocities vary from about 0.5 to 1 knot, depending upon the cross section of the Bay. In general, currents parallel the long axis of the Bay, although there is evidence of rotary tidal currents in broader sections. Due to the weakness of river and tidal currents, they are often overcome completely and reversed in direction by local winds.

Mean tidal ranges of 1.0, 1.1 and 1.2 ft. are reported for Sevenfoot Knoll, Ft. McHenry and Pratt and Light Streets, respectively, in

[15] Haight, F. J., *et. al.*, Tides and Currents in the Chesapeake Bay and Tributaries, U.S.C. and G.S. Special Publication 162 (1930).
* 1 knot equals 1.15 statute miles per hour or 1.69 feet per second.

the Port of Baltimore itself. An extreme tidal range approaching 13 ft. has been recorded. Recent data from records of the City's automatic tide gage on Pier 7, Northwest Branch, are presented in Table 11. A simultaneous H.W. and a mean tidal range of 1.1 ft. have been assumed.

TABLE 11

BALTIMORE HARBOR TIDES, 1940–1949

Year	*Tidal Heights Relative to City Datum, ft.**			
	Mean L.W.	*Mean H.W.*	*Maximum L.W.*	*Maximum H.W.*
(1)	(2)	(3)	(4)	(5)
1940	+0.51	+1.73	—3.1	+3.6
1941	+0.42	+1.59	—2.5	+3.5
1942	+0.50	+1.70	—2.0	+4.6
1943	+0.53	+1.70	—2.5	+3.4
1944	+0.46	+1.55	—2.2	+3.4
1945	+0.52	+1.66	—2.5	+4.5
1946	+0.70	+1.77	—1.9	+3.8
1947	+0.57	+1.66	—2.7	+3.9
1948	+0.75	+1.90	—2.2	+4.0
1949	+1.05	+2.12	—1.8	+4.0

* From Baltimore Bureau of Harbors Annual Reports. City Datum is 0.3 ft. below local mean low water.

Examination of tide gage records for the Patapsco Estuary discloses three types of water level variation. First, there is a direct wind response. Northwesterly winds tend to drive water out of the Harbor and cause unusually low tides. Water is piled into the region by southeasterly winds. Similar effects are noted on a larger scale on the Bay and produce water level fluctuation at Baltimore. A second type includes the seiches which follow the heaviest storms. Usually low tides are generally followed by higher than normal tides as water floods to an area under the influence of gradients produced by the initial storm. If such oscillations in the Bay are large, they often overcome the effects of secondary winds within the Harbor. The third category, astronomical tide, is superimposed on both of the foregoing phenomena. In Fig. 7 there is reproduced a recent succession of local tides and all of these categories of water surface variation are discernible.

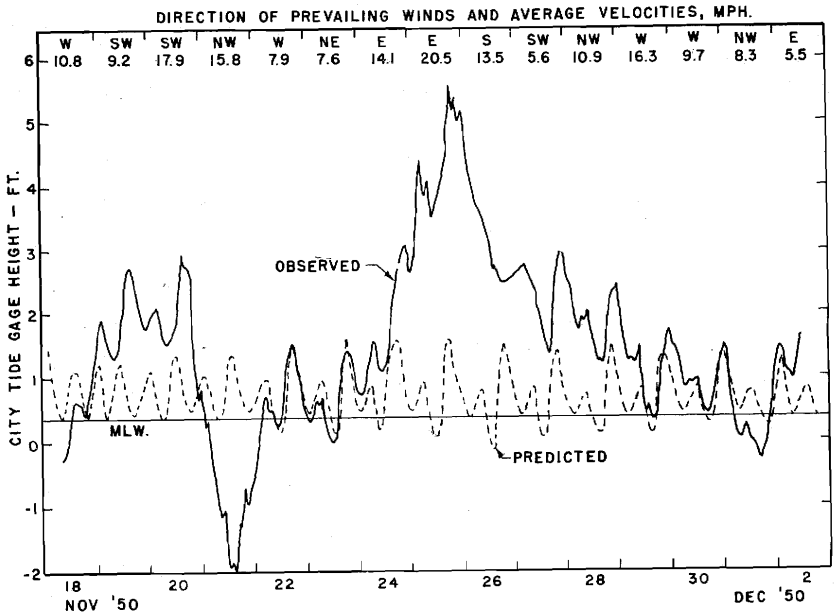


Fig. 7. BALTIMORE HARBOR TIDES, Nov. 18—Dec. 2, 1950
(City Bureau of Harbors Tide Gage, Pier 7, Northwest Branch)

Tidal Currents

The horizontal forward and backward water movement which accompanies the tide is called the tidal current. During a tidal cycle and under the influence of tidal forces alone, a water particle moves horizontally over a distance equivalent to the tidal excursion (distance traversed by a water particle on the flooding tide)—given by the expression:

$$s = v \times \frac{T}{2}$$

where s = the distance traversed,
T = the tidal period, averaging 12.42 hrs., and
v = the mean velocity during the half-tidal period in which flow occurs.

In Appendix E it is shown that for the local mean tidal range of 1.1 ft:

$$v = \frac{S}{A} \times 4.9 \times 10^{-5} \text{ fps.}$$

where S = the surface area (sq. ft.) above any reference transverse section, and

A = the area (sq. ft.) of the section.

Consider now a section across the mouth of the Harbor between North Point and Rock Point. Here A = 170,000 sq. ft. and $S = 905 \times 10^6$ sq. ft. Substituting these values in the above expressions, the mean velocity (v), calculates to be 0.26 fps. and the tidal excursion is 1.1 miles. Thus, most of the water moving inward through the Harbor entrance under the influence of tidal forces alone does not penetrate the region to any significant extent.

From the properties of the cosine curve which closely describes the variation of tidal currents:

$$V = \frac{\pi}{2} \times v$$

where V = the current at strength.

From this and the further assumption that mid-channel currents are one-third greater than mean velocities, the mid-channel current at strength on the above section calculates to be 0.54 fps., or 0.32 knots. This agrees with the figure of 0.3 knots reported by the U.S.C.&G.S. for mean strengths of current at this general location. In the same manner, it can be shown that tidal currents above Sparrows Point and in Harbor tributaries are negligible. This, too, agrees with observation and indicates the minor influence of astronomical tides on water movement at Baltimore.

Wind-generated Currents

The current surveys of this investigation disclosed a circulation pattern which is not evident from study of tidal data alone.

It has been indicated that the main channel constitutes the effective transverse section at Ft. Carroll, mid-way down the Harbor. The data of Fig. 8 were obtained during a current survey from an anchored channel position on a line between the Hawkins Pt. light and the Fort. Under the influence of moderate northerly breezes averaging 14 mph., river and tidal forces were entirely overcome and upper water layers moved downstream through the section for the entire period of observation. A compensating inward bottom current averaging about 0.2 fps. was developed in the dredged portion of the section. Measurements made at 20 ft. disclosed only weak and irregular currents. The channel section below 20 ft. at this location has an area of about 12,000 sq. ft. So, assuming a mean velocity for the entire area of one-half that observed at its center, the countercurrent of Bay water amounted to 1,200 cfs. This is about three times the average summer rate of upland drainage to the Port.

The results of current observations obtained during the previous week at the same location illustrate intermediate circulation characteristics, Fig. 9. Tidal currents were more evident on this day, particularly below the surface. But surface water to a depth of at least four feet responded promptly to the change of wind direction which occurred between 0900 and 1000 hours.

Observed Chlorinity Distributions and Their Significance

An almost limitless variety of salinity distributions can develop within the Baltimore Harbor as a result of the complex interplay of forces due to tides, winds and river runoff. Thus, definition of mean conditions for the Estuary perforce involves long-time observation impossible in terms of this study. Comprehensive prior information is lacking and interpretation of instantaneous distributions is frequently confusing, because the chlorinity source for the region, the Chesapeake Bay, is itself a very much larger and more complicated estuary. However, examination of information at hand is of value.

Three types of field chlorinity investigations were conducted: chlorides were determined on all water samples collected routinely from 13 stations established over the region (Cf. Fig. 14 for detailed locations), brackish-water distribution on a longitudinal main-channel section received special study, and transverse distributions were determined on three representative Harbor sections. Figures 10 through 13 summarize these data, and complete profile results are given in Appendix G. Representative chloride-depth curves are presented in Fig. 21. These observations are summarized and interpreted as follows:

(1) Harbor chlorides are characterized by a rythmic seasonal variation. This is attributed to a similar fluctuation of Bay-water salinities off the entrance to the Port, rather than to any marked influence of Patapsco River flows. Upper Bay salinities are an inverse function of discharge from the 27,400 sq. mi. Susquehanna River watershed, being a maximum in the fall of the year when upland drainage is low and a minimum in the spring when stream discharge is high. Good correlation has been demonstrated between

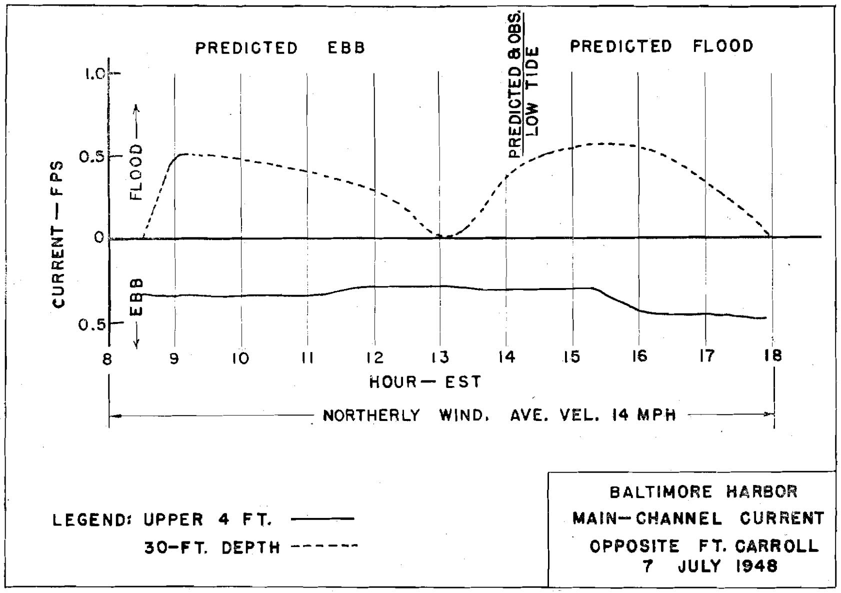

PREDICTED EBB
PREDICTED & OBS. LOW TIDE
PREDICTED FLOOD
CURRENT — FPS
FLOOD
EBB
1.0
0.5
0
0.5
8
9
10
11
12
13
14
15
16
17
18
HOUR — EST
NORTHERLY WIND, AVE. VEL. 14 MPH
LEGEND: UPPER 4 FT.
30-FT. DEPTH
BALTIMORE HARBOR
MAIN-CHANNEL CURRENT
OPPOSITE FT. CARROLL
7 JULY 1948

Fig. 8.

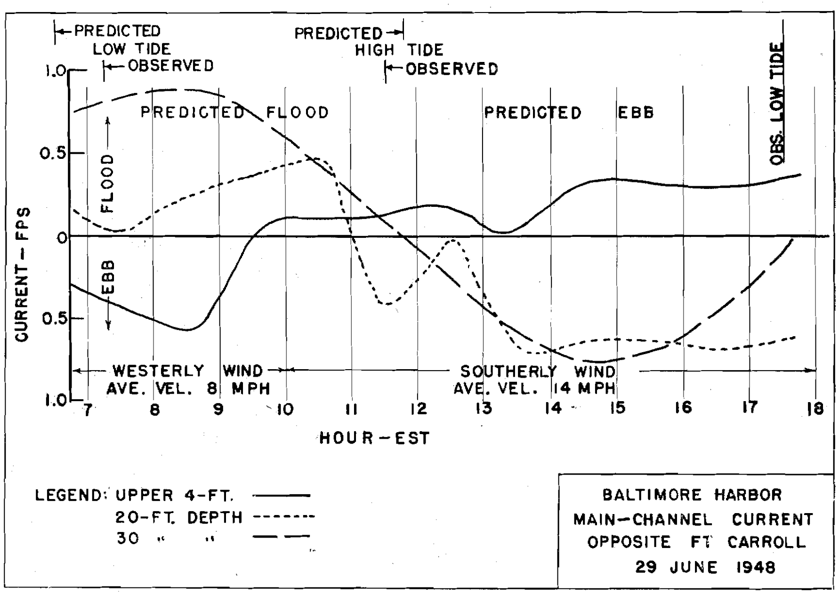

PREDICTED
LOW TIDE
OBSERVED
PREDICTED
HIGH TIDE
OBSERVED
OBS. LOW TIDE
PREDICTED FLOOD
PREDICTED EBB
CURRENT — FPS
FLOOD
EBB
1.0
0.5
0
0.5
1.0
WESTERLY WIND
AVE. VEL. 8 MPH
SOUTHERLY WIND
AVE. VEL. 14 MPH
7
8
9
10
11
12
13
14
15
16
17
18
HOUR — EST
LEGEND: UPPER 4-FT.
20-FT. DEPTH
30 " "
BALTIMORE HARBOR
MAIN-CHANNEL CURRENT
OPPOSITE FT CARROLL
29 JUNE 1948

Fig. 9.

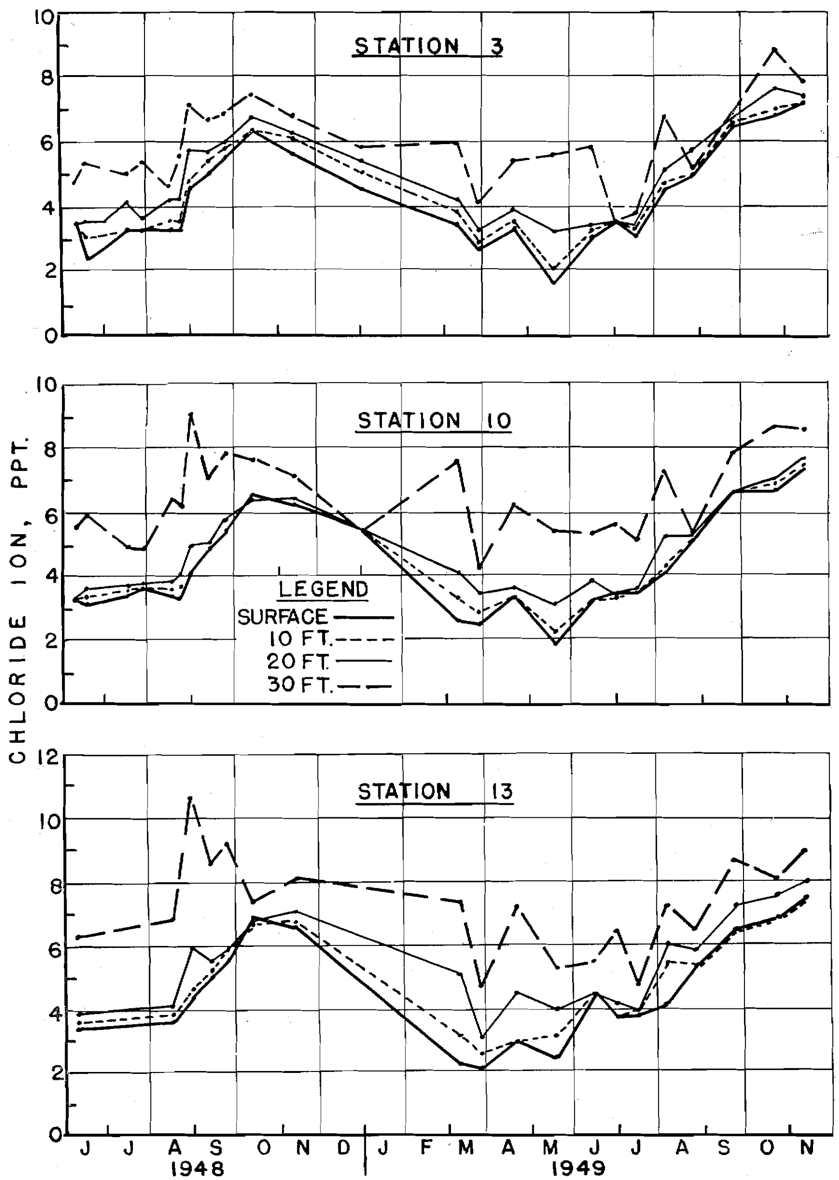


Fig. 10 Baltimore Harbor: SEASONAL MAIN—CHANNEL CHLORIDE VARIATION

Susquehanna discharges and Harbor salinities recorded by the U.S.C.&G.S. for water off Fort McHenry.[16]

(2) The mean longitudinal chlorinity gradient in the Patapsco Estuary is almost nil. Bottom water in the fairway freshens slightly toward the Inner Harbor. This is in accord with the hypothesis that the direction of its net motion is inward and that turbulence adds to this flow a certain amount of less saline supernatant water. The flatness of the surface gradient appears to be largely due to local topography. The lower portion of the main channel is believed to function as a conduit for the transport of saline bottom water to the virtual head of the Estuary off Ft. McHenry. Here, this relatively high-saline water is mixed with overlying water which discharges downstream with no significant accretion of water from the lower portion of the main channel. Furthermore, float surveys conducted by the Baltimore Sewerage Commission show that the region below Sparrows Point is subject to freshening by inward transport of Bay surface water.[17]

(3) The vertical chlorinity distribution varies between two extremes. At times, horizontal transverse mixing is complete, but positive and vertical linear gradients exist. On the other hand, water at any location is occasionally uniformly mixed horizontally and vertically. A more common intermediate situation is observed in which water is homogeneous to a variable depth, generally betwen 10 and 20 ft. Linear vertical stratification is believed to be characteristic in the absence of wind circulation and its attendant mixing. Recalling that natural water depths average between 10 and 20 ft., the intermediate distribution is attributed to effective wind stirring to the undredged bottom. This reasoning is supported by correlation between wind velocities and the presence and depth of the halocline. Stratification develops during periods of calm weather (winds 0 to 3 mph.) and is destroyed in a matter of hours following higher-velocity-winds—especially those prevailing for a day or more from directions roughly parallel to the long axis of the Port. Winds of velocity 10 to 15 mph. are able to mix water vertically to the natural bottom, while uniform mixing to the channel bottom some 20 ft. deeper is produced by less frequent stronger winds.

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[16] Beaven, G. Francis, Effect of Susquehanna River Stream Flow on Chesapeake Bay Salinities and History of Past Oyster Mortality on Upper Bay Bars, Contribution No. 26, Chesapeake Biol. Lab. (1946). Reprinted from 1946 Annual Report, Md. Bd. of Natural Resources.

[17] Allen, Kenneth, discussion of paper by H. deB. Parsons, Tidal Phenomena in New York Harbor, Trans. Am. Soc. of Civil Engrs., 76:1979 (1913) pp. 2039 *et seq.*

Flushing of the Region

Flushing of Baltimore Harbor is an extremely complex and dynamic phenomenon. It is the net result of local interplay of the river, tidal and wind effects and of Chesapeake Bay conditions off the mouth of the River. While it is impossible to predict this net result quantitatively, it is illuminating to consider what may be accomplished by each of the forces operating.

(1) **River Flow:** The Harbor volume, exclusive of tributaries, is about 11,000 x 10^6 cu. ft. and the maximum mean monthly potential flow of the Patapsco approaches 1,000 cfs. At this flow, a particle of river water would require an average of

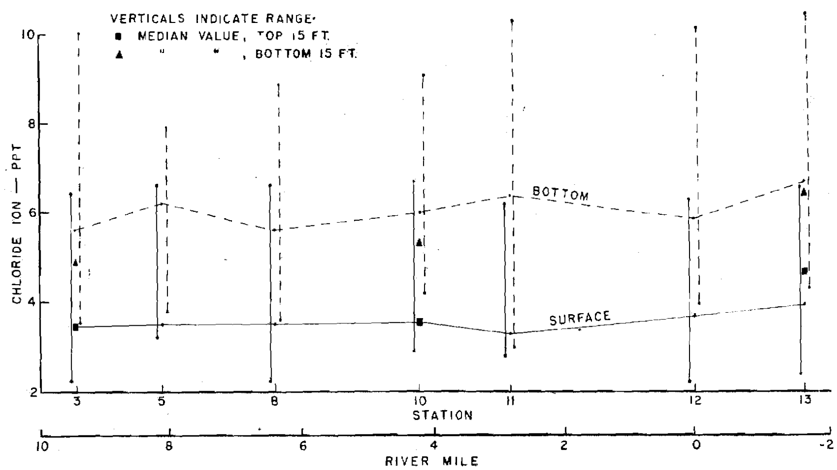


Fig. 11.

Baltimore Harbor

MEDIAN MAIN-CHANNEL SUMMER CHLORIDES
1947-49

$$\frac{11{,}000 \text{ x } 10^6}{1{,}000 \text{ x } 86{,}400} = 128 \text{ days}$$

or about four months to travel from Ft. McHenry to the Bay in the absence of tides and winds. On the same basis, the flushing time for the mean summer discharge of 416 cfs. would be 1000/416 times as long—about 10 months.

(2) **Tidal Flushing:** Two methods for determining the flushing or flow-through time of an estuary have been mentioned. One of these involves determination of river-water accumulation in the

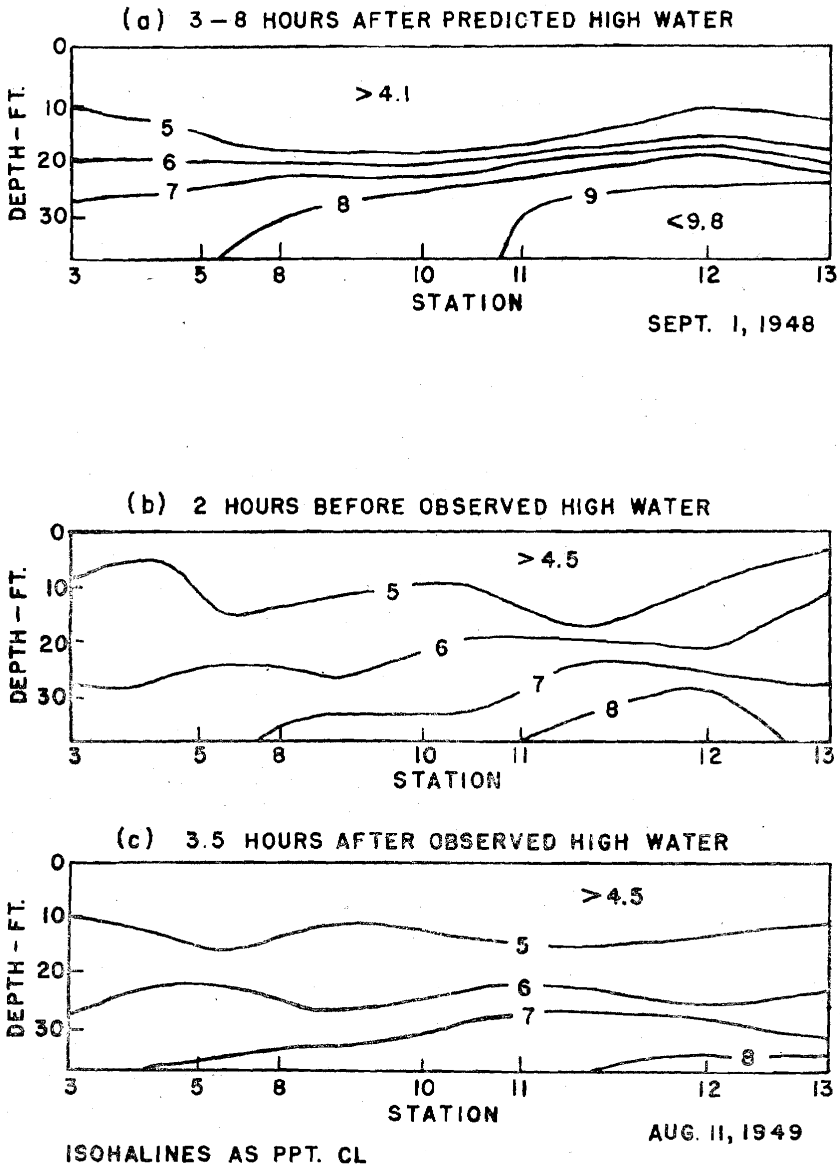


Fig. 12.

Baltimore Harbor

ISOHALINES FOR MAIN-CHANNEL SECTION

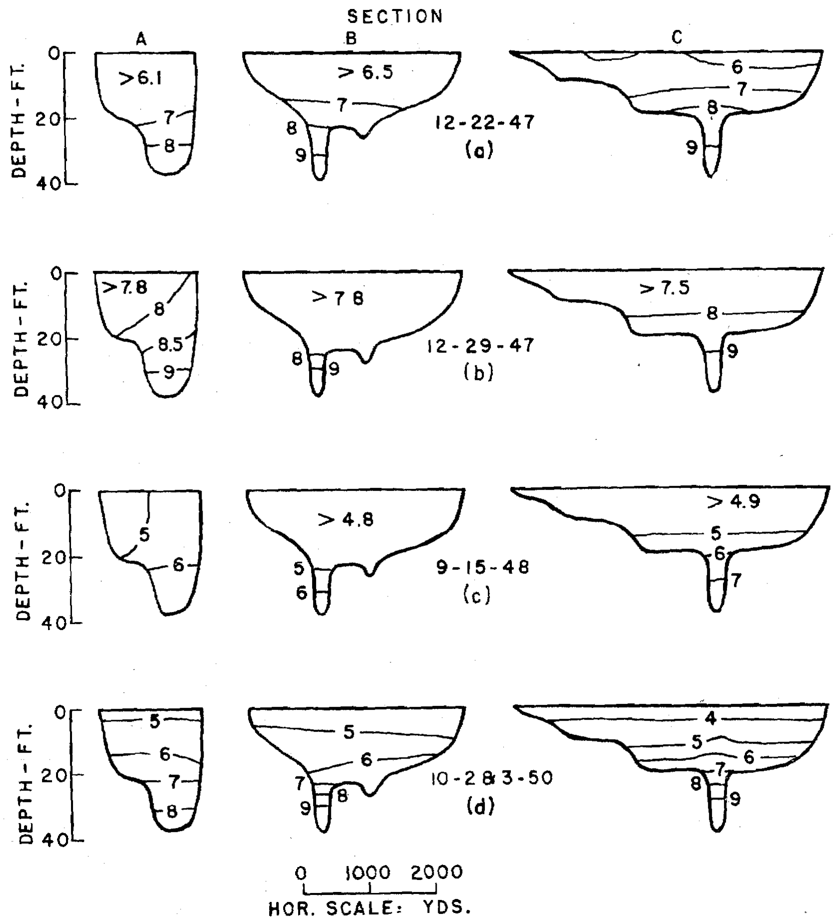


Fig. 13.

Baltimore Harbor

ISOHALINES ON TRANSVERSE SECTIONS

Isohalines as ppt. Cl^-

Section A runs between Lazaretto Pt. and Fairfield.
Section B runs between Sparrows and Hawkins Pts.
Section C runs between North and Rock Pts.

estuary from field observations. It has been shown that the summer chloride content of upper water strata in the Harbor averaged about 3.8 ppt. during the study, while a similar value for bottom water (lower portion of main channel) was 6.0 ppt. Assuming that upper water is a simple mixture of Patapsco River water and Bay bottom water, the fraction of fresh water in the upper stratum is given by the expression:

$$F = \frac{S - S_o}{S}$$

where F = the fraction of fresh water present in the brackish-water dilution,

S = the chloride content of the undiluted brackish water, and

S_o = the observed chloride content of the dilution.

The fraction is 0.367 for the situation under consideration and the Harbor volume is 8×10^9 cu. ft., exclusive of tributaries and the volume below 16 ft. Summer river flow averages 416 cfs. or 36×10^6 cu. ft. per day, so that the flushing time for these conditions is:

$$\frac{0.367 \times 8 \times 10^9}{36 \times 10^6} = 81 \text{ days}$$

This computation has two disabilities. First, the assumption is required that all fresh water in the region is derived from the Patapsco. It has been mentioned that Susquehanna River and possibly additional fresh-water fractions are brought into the region to an unknown extent. The second factor, which also influences chloride-ion concentrations, is the discharge of chloride-bearing industrial wastes to the Inner Harbor. On the average, however, the latter is not felt to be of serious import.

The Ketchum hypothesis, details of which are given in Appendix E, indicates a flushing time for summer conditions at Baltimore of slightly over 100 days. It should be noted that local topography complicates application of the technique and that it is impossible to include important local wind effects.

(3) **Wind Flushing:** The cycle of events illustrated in Fig. 7 has real significance and merits more detailed examination. On November 19, 1950, the Harbor water surface rose to nearly three feet above MLW. and then dropped 4.9 ft. in 24 hrs. This indicates an estimated discharge from the Estuary of 4.6×10^9 cu. ft. of water. (Cf. Appendix E). Then the 7-ft. rise which developed between the 21st and 25th represents an inflow to the Port of 8.2×10^9 cu. ft. The ensuing four days saw a return of water surface elevations to normal, indicating a net discharge of 6.9×10^9 cu. ft. Assuming complete mixing, it can be shown that about one-half of the water in the area at the beginning of this sequence of events was removed during the ensuing 10 days. Although this particular situa-

tion is extreme, it exemplifies the "breathing" mechanism through which the Port is flushed by wind forces.

The extent and frequency of this effect is not discernible from calculations of mean tidal range since this value is the average difference in successive heights of high and low water. Examination of tide-gage records for the Harbor discloses that moderate breezes (13 to 18 mph.) are capable of affecting the water level in the Estuary. Gross oscillations exist, too, which cannot be correlated satisfactorily with local wind data. It may be stated, however, that tremendous volumes of Bay water are moved in and out of the Harbor by this mechanism.

It has been mentioned that in addition to this more or less direct wind flushing there is another type which need involve no changes in volume of water in the Harbor. Surface water is driven in or out of the Estuary by winds and subsurface return currents are generated which tend to maintain the water volume in the region. Assumption of reasonable values for these currents in the lower portion of the main channel discloses that they would have to persist in one direction for over two months in order to flush the region completely. Since this type of circulation does not persist for such long periods, it cannot be counted on to accomplish periodic complete flushing.

SUMMARY

The river, tidal and wind processes controlling water circulation in Baltimore Harbor are reasonably well understood individually and qualitatively. The end result is produced by simultaneous interaction of these constantly and independently varying forces in a complex manner manner for which no simple solution is possible.

In terms of the fundamental questions posed at the outset of this section of the report, the Harbor hydrography is summarized as follows:

a. It is impracticable to attempt from available information to offer quantitative estimates of the dilution available for waste disposal in the Harbor. The potential summer land-water discharge through the Estuary approaches 400 cfs. or about 260 mgd. However, source water for the region appears to derive principally from Chesapeake Bay and is brought into the Estuary largely by unpredictable wind forces.

Random local winds are sufficient to overcome frequently the weak current system generated by mixing of Patapsco River discharge and brackish water from Chesapeake Bay under the influence of mean tides of only 1.1 ft. Practically, then, overall stirring and mixing processes are generally effective to the depths of the undredged bottom which ranges from 10 to 20 ft.

b. Water circulation within the Estuary, as concerns possible diffusion patterns, is so dominated by wind forces that no Harbor location is sure always to be unaffected by waste discharge at any other point within the region.

c. Predominance of wind effects also introduces a large element of uncertainty into quantitative appraisal of flushing times for the region. It is clear that water exchange in peripheral sections is negligible. Since fresh-water runoff into these portions of the Harbor is small, flushing by flow of streams is unreliable and slow. On a larger scale, the same is true of the main Estuary. There is indication that flushing of the Estuary due to all causes normally averages several weeks. The time varies widely but is less in summer than in winter because of the seasonal distribution of winds. The Harbor below Sparrows Point is doubtless flushed more effectively than inner regions. Heavy storms appear to effect drastic ventilation of the entire basin within a few days.

Section V.

POLLUTION GRADIENTS

Two of the fundamental factors that influence the quality of water in Baltimore Harbor, pollution load and stream hydrography, have been considered independently. The manner in which these and other factors affect present water-quality conditions is now to be treated.

Intensive water sampling during periods of steady stream regimen, in fresh water studies, sometimes yields data which, together with waste discharge and hydrographic information, enable computation of mathematical parameters which define the capacity of natural streams to assimulate organic material. It is then possible to predict probable conditions under changed loading. In the case of estuaries where tides and river discharge alone are the dominant forces producing water circulation, similar computations can be made. It was anticipated at the beginning of this study that collection of appropriate data would serve as a basis for such computations. It became increasingly evident as the work progressed, however, that both land-water runoff and tides have relatively little to do with circulation in Baltimore Harbor. As already noted, water movement in the Estuary is induced primarily by unpredictable wind forces. Under these circumstances only an extensive water sampling program, continued over a period of many years, will yield information wholly adequate to define conditions.

The Sampling Program

An ideal water sampling program for estuarine conditions would provide synoptic and instantaneous information of an accuracy suited to the purpose at hand. For a large water area, it is hardly possible to carry out such a program because of the number of men, boats and instruments which would be needed. Any practical study, therefore, involves compromises between cost, time, accuracy and amount of basic data.

It was considered desirable to limit field operations in this investigation to those which would enable coverage of the Estuary within one day. Preliminary investigation disclosed a reasonable uniformity of conditions on transverse sections. In addition,

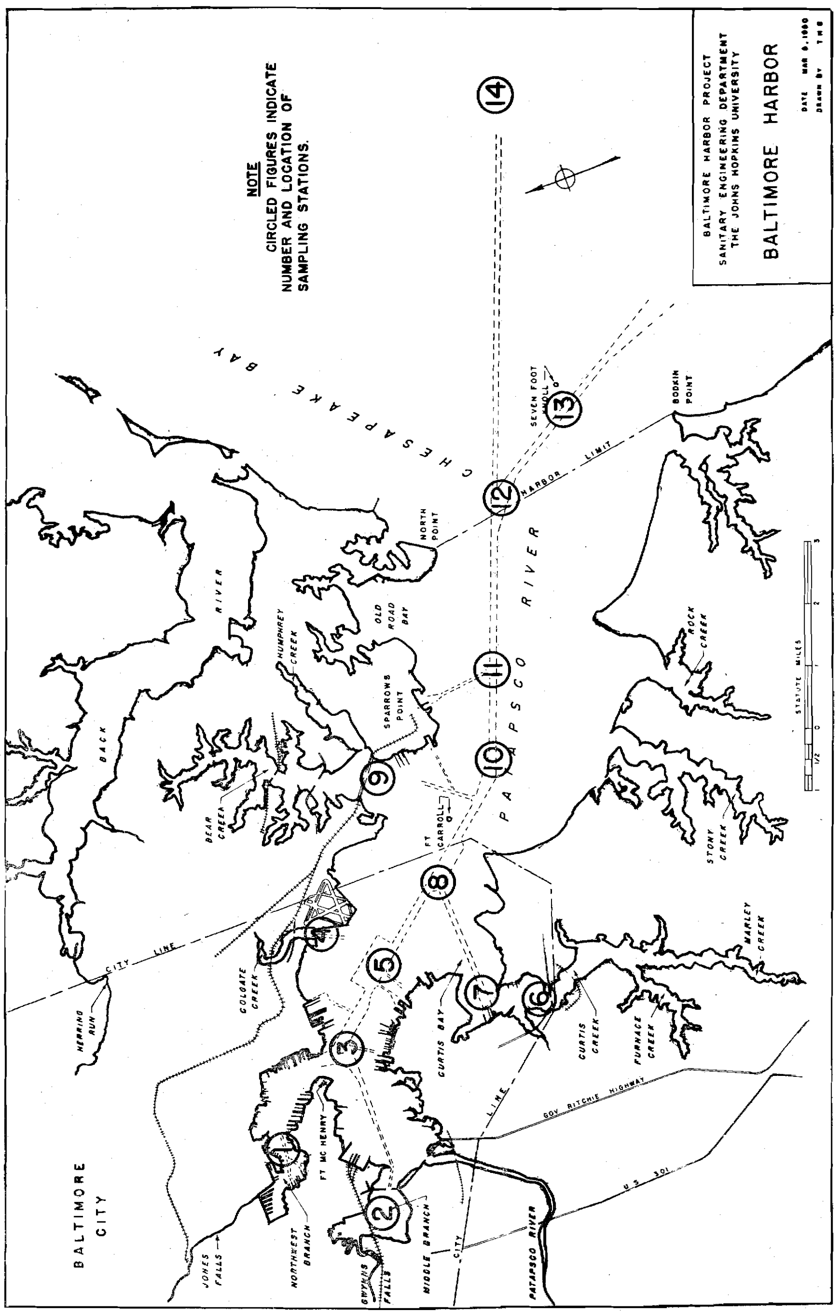


Fig. 14.
WATER SAMPLING STATIONS

Harbor topography is such that it seems logical to assume that water movement occurs principally in the general vicinity of main channels. Accordingly, 13 routine sampling stations were established as shown in Fig. 14. Stations were visited as frequently as practicable. During field phases of the investigation, attempt was made to adhere to a schedule of monthly winter sampling and biweekly sampling in the intervening weeks.

Routine analytical determinations and their units of reporting were as follows:

(1) Temperature, centigrade degrees (°C.)

(2) Chlorides, parts per thousand (ppt.) as Cl^-.

(3) pH

(4) Dissolved oxygen, parts per million (ppm.) and percent of saturation.

(5) Biochemical oxygen demand, ppm. at 20°C. in 5 days.

(6) Total iron, ppm. as Fe.

(7) Alkalinity, ppm. as equivalent $CaCO_3$.

(8) Acidity, ppm. as equivalent $CaCO_3$.

(9) Coliform bacteria, most probable number (M.P.N.) per 100 ml.

Conductivity measurements proved to be useful in the study of salinity distributions. Total and volatile solids and content of ether-soluble material were run on bottom mud samples.

Laboratory techniques conformed, as far as practicable, to the latest standard methods published jointly by the American Public Health Association and the American Water Works Association.[18] Special field and laboratory procedures are presented in detail in Appendix B. Analytical data accumulated during the investigation will be found in Appendices F through H.

Water Quality

Temperature

Water temperatures in Baltimore Harbor closely parallel local air temperatures. Inner Harbor water is commonly one or two

[18] Standard Methods for the Examination of Water and Sewage, American Public Health Association and American Water Works Association, New York. (9th Edition, 1946).

centigrade degrees warmer than that in the Lower Harbor, probably because of less mixing with cooler Bay water and of a relatively greater use in this section of water for industrial cooling. Fig. 15 presents temperature data for two selected stations and illustrates the correspondence between air and water temperatures.

The shallowness of the Harbor and Bay and the effectiveness of mixing to the depth of the undredged bottom permit ready equalization of air and water temperatures to that depth. During spring and summer, the temperature of deep water in the bottom of the main channel lags behind that of upper water in following rising air temperatures. Vertical gradients measured during these months exhibited the inflection also characteristic of chlorinity and dis-

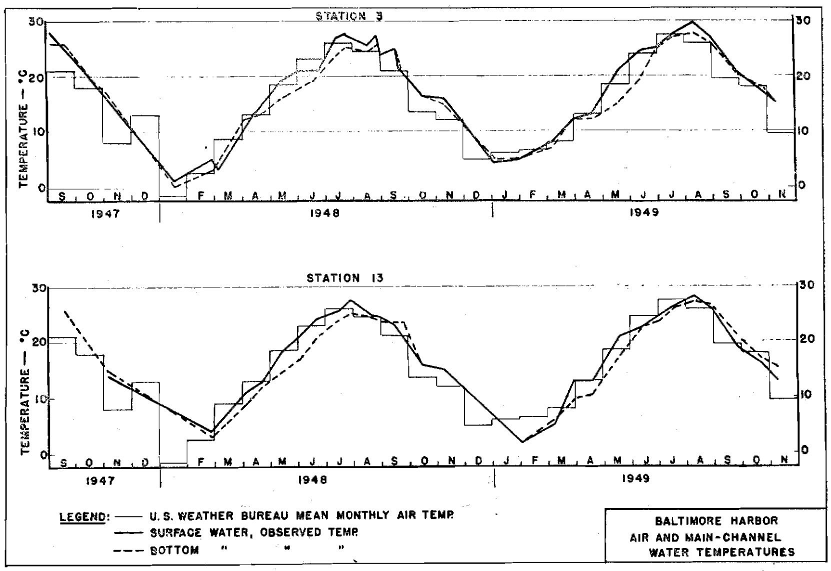


Fig. 15.

solved oxygen. Differences of as much as 5 to 6°C. between top and bottom temperatures were encountered. Ordinarily, however, this difference was rarely more than 3°C. in the deepest portion of the Harbor.

Table 12 indicates that median summer (June through September) surface and bottom-water temperatures ranged during this study from 24 to 26°C. for all stations. Maxima of 27°C. were encountered at outer stations and 30°C. in the Inner Harbor.

TABLE 12

BALTIMORE HARBOR: SUMMER WATER TEMPERATURES 1947-49*

*Station***	*Number of Samples*	*Observed Temperature, °C.*		
		Maximum	*Median*	*Minimum*
(1)	(2)	(3)	(4)	(5)
1–T	13	29	25	20
–B	13	28	25	20
2–T	12	30	26	19
–B	12	28	24	20
3–T	18	30	26	21
–B	21	28	25	18
4–T	13	30	25	20
–B	15	28	25	20
5–T	9	29	25	20
–B	9	28	24	20
6–T	12	29	25	20
–B	14	28	24	20
7–T	13	28	25	21
–B	16	27	25	17
8–T	13	29	25	20
–B	16	28	24	17
9–T	15	29	26	20
–B	13	29	26	22
10–T	16	29	25	20
–B	19	28	24	19
11–T	10	27	24	19
–B	13	27	24	16
12–T	12	28	25	19
–B	13	27	24	17
13–T	14	28	24	19
–B	16	27	24	17

* June through September.
** T = surface; B = bottom.

Fig. 15 shows that winter water temperatures approach freezing. The cold weather of 1947-48 was unusually severe and ice cover in the Estuary then was about as extensive as it ever gets. The Port freezes over about once every ten years.

Chlorides and Salinity

The chloride content of the Harbor water has been discussed in detail in Section IV. It exhibits a characteristic seasonal fluctuation from a high in the fall of the year to a low in the spring. During this study, surface-water chlorinity (as Cl^-) ranged from about 1.5

to 7 ppt. and bottom-water chlorinity from about 3.6 to 10 ppt. Summer conditions are presented in Table 13.

TABLE 13

BALTIMORE HARBOR: SUMMER CHLORIDES
1947–49*

Station**	Number of Samples	Observed Chlorides, ppt. as Cl^-		
		Maximum	*Median*	*Minimum*
(1)	(2)	(3)	(4)	(5)
1–T	13	6.6	3.8	2.3
–B	13	6.8	4.0	3.3
2–T	12	6.5	2.8	0.9
–B	15	6.7	3.6	1.8
3–T	18	6.4	3.4	1.5
–B	19	10.0	5.6	3.5
4–T	14	6.5	3.3	2.5
–B	16	6.6	3.8	3.1
5–T	9	6.6	3.5	3.2
–B	9	7.9	6.2	3.8
6–T	13	5.9	3.4	2.9
–B	15	7.4	4.8	3.0
7–T	14	6.3	3.4	3.0
–B	15	11.8	5.6	3.7
8–T	14	6.6	3.5	2.2
–B	15	8.9	5.6	3.6
9–T	16	8.5	3.2	2.4
–B	15	6.6	3.4	3.1
10–T	16	6.7	3.6	2.9
–B	17	9.1	6.0	4.2
11–T	12	6.2	3.3	2.8
–B	13	10.4	6.4	3.0
12–T	13	6.3	3.7	2.2
–B	14	10.2	5.9	4.0
13–T	14	6.6	4.0	2.4
–B	15	10.7	6.7	4.3

* June through September.
** T = surface; B = bottom.

The U. S. Coast and Geodetic Survey has measured the density and temperature of surface water near Fort McHenry daily since 1914.[19] From the relationships between density, temperature and salinity (content of dissolved salts) for full sea water, it reports mean monthly salinities for the period 1914-18 ranging from 10.6 ppt. in November to 5.6 ppt. in May.* The maximum salinity of

[19] DW-1, Density of Sea Water at Coast and Geodetic Survey Tide Stations, Atlantic and Gulf Coasts, U. S. Dept. of Commerce, (Revised 1949).
* The salinity-chloride ratio for Baltimore Harbor is about two. This is slightly higher than that for full sea water, probably largely because of accumulations of soluble wastes in the Estuary.

record, 18.3 ppt., was observed during the drought of 1930-31. A minimum salinity of 1.8 ppt. was recorded in 1936 at this station.

pH, Alkalinity and Acidity

The reaction or pH of polluted water is a more significant measure of acid or alkaline pollution than total acidity or total alkalinity. These three water-quality characteristics are so closely related they are treated together.

Water in the Port is normally alkaline. Due to the distribution of saline water, deep water has a somewhat higher alkalinity than supernatant water. In addition, a minor seasonal variation is evident which parallels the salinity fluctuation noted previously. Normal alkalinities for the Estuary average approximately 50 ppm. as equivalent $CaCO_3$ and ranged during this investigation from about 25 to 85 ppm.

The waste survey shows that variation in pH, alkalinity and acidity of the waters of the Port result almost exclusively from discharge of acidic industrial wastes and that loading of this nature is concentrated principally in the highly industrialized Curtis Bay-Fairfield area. Other important sources of acid exist on Colgate Creek and at Sparrows Point. In these peripheral areas where flushing is poor, accumulation of acid exhausts the neutralizing capacity of the Harbor water.

Analyses of pH data are given in Table 14 and Figs. 16 and 17. At the mouth of Colgate Creek (Station 4), pH values less than 4.0 were encountered nearly one-third of the time. Minimum values found here were 2.5 for bottom water and 3.1 for surface water. Detailed sampling in Colgate Creek during the summer of 1948 showed that pH values for the entire stream ranged closely around 3.0. Total acidities up to 750 ppm. (mineral acidity, 394 ppm.) were encountered.

About one-half of the samples collected in Curtis Bay had a pH below 5.0 and approximately half of these exhibited a reaction below 4.0. Minimum values found were 2.8 at the bottom and 3.4 for surface water. Total acidities up to 404 ppm. and mineral acidities up to 160 ppm. were measured in this area. Effects of acidic industrial discharges here extend inland to the head of navigable water in both Furnace and Marley Creeks. pH values of 5.6 and 5.1 were determined on August 4, 1948 for water at Marley bridge on Marley Creek and the head of navigation on Furnace Creek, respectively.

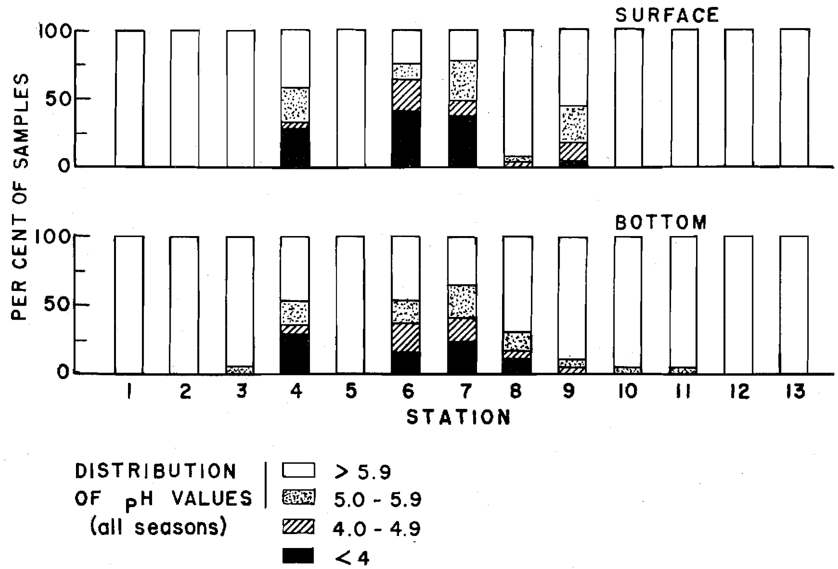


Fig. 16.

Baltimore Harbor

pH DISTRIBUTION

1947-49

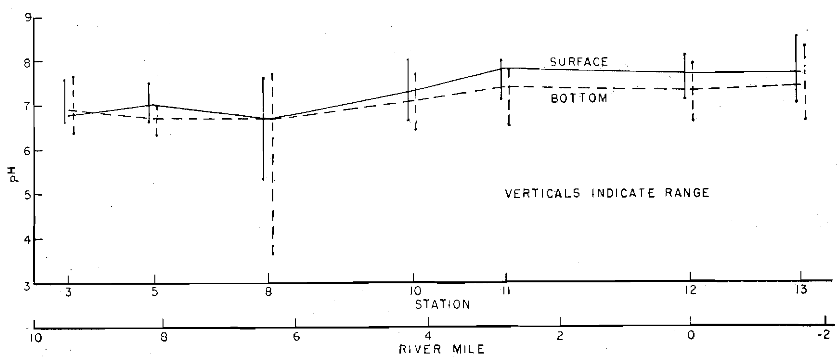


Fig. 17.

Baltimore Harbor

MEDIAN MAIN-CHANNEL SUMMER pH

1947-49

TABLE 14

BALTIMORE HARBOR: SUMMER pH, 1947-49*

Station**	Number of Samples	Observed pH		
		Maximum	Median	Minimum
(1)	(2)	(3)	(4)	(5)
1–T	12	7.4	6.9	6.8
–B	12	7.2	6.8	6.7
2–T	12	7.5	6.8	6.7
–B	12	7.7	6.8	6.6
3–T	17	7.6	6.8	6.6
–B	18	7.7	6.8	6.4
4–T	13	7.1	5.7	3.1
–B	14	7.8	5.8	2.5
5–T	9	7.5	7.0	6.6
–B	9	7.0	6.7	6.3
6–T	12	6.3	3.8	3.4
–B	13	7.2	5.0	3.1
7–T	13	6.6	3.9	3.5
–B	14	7.0	5.4	2.8
8–T	13	7.6	6.7	5.3
–B	14	7.7	6.7	3.6
9–T	14	7.2	5.8	3.9
–B	14	7.6	6.8	4.8
10–T	15	8.0	7.3	6.6
–B	16	7.7	7.0	6.4
11–T	11	8.0	7.8	7.1
–B	12	7.8	7.4	6.5
12–T	12	8.1	7.7	7.1
–B	13	7.9	7.3	6.6
13–T	13	8.5	7.7	7.0
–B	14	8.3	7.4	6.6

* June through September.
** T = Surface; B = bottom.

Water became progressively acid downstream until a minimum of pH of 2.8 (mineral acidity 106 ppm.) was encountered from bottom water off Sledds Point in Curtis Bay. Total acidities were determined by titration to phenolphthalein end point (pH 9±) and mineral acidities were determined by titration to methyl orange end point (pH 4±).

During the period of field study, the steel mill on Sparrows Point disposed of large quantities of waste pickle liquor to Bear Creek—directly and indirectly through Humphrey Creek. Direct discharge of this waste to Bear Creek no longer occurs. Water exchange in Bear Creek is poor and pH values from 4.5 to 6.2 were found opposite the mill in the summer of 1948. About 50 per cent of samples collected below the first bridge (Station 9) were below pH 5.0.

Dilution in the alkaline waters of the fairway was sufficient during this investigation to neutralize present acidity loadings. The reaction of main-channel water off Curtis Bay was occasionally depressed by waste discharges—particularly bottom water at this location. In general, however, the reaction of the main Estuary centered around neutrality and ranged from about 6.3 to 8.5 (Fig. 17).

Biochemical Oxygen Demand

Warm-weather B.O.D. data are summarized in Table 15. The distribution of observed values is presented in Fig. 18 and conditions in the principal portion of the Estuary appear in Fig. 19.

TABLE 15

BALTIMORE HARBOR: SUMMER BIOCHEMICAL OXYGEN DEMAND 1947-49*

*Station***	*Number of Samples*	*Observed 5-day, 20° C. Biochemical Oxygen Demand*		
		Maximum	*Median*	*Minimum*
(1)	(2)	(3)	(4)	(5)
1–T	11	7.2	3.5	1.8
–B	12	3.7	2.0	1.3
2–T	11	6.0	3.3	2.5
–B	12	2.2	1.6	0.4
3–T	13	7.9	2.1	1.4
–B	14	2.6	1.4	0.7
4–T	13	10.5	1.9	0.5
–B	14	2.5	1.6	0.9
5–T	9	2.6	1.9	1.3
–B	9	2.6	1.1	0.5
6–T	11	5.7	2.4	0.9
–B	13	8.4	1.5	0.5
7–T	13	5.9	2.0	0.6
–B	16	4.4	1.2	0.0
8–T	13	2.9	1.8	0.7
–B	14	2.4	1.4	0.0
9–T	15	4.1	1.5	0.9
–B	14	2.1	1.4	0.1
10–T	11	4.0	1.9	0.7
–B	12	2.6	1.3	0.6
11–T	11	3.9	2.2	0.4
–B	12	3.1	1.2	0.2
12–T	12	4.1	2.4	1.4
–B	13	4.5	1.4	0.4
13–T	10	3.8	2.2	0.9
–B	11	4.3	1.4	0.9

* June through September.
** T = surface; B = bottom.

The B.O.D. of Baltimore Harbor water in general is low. Organic waste discharges occur for the most part in inner portions of the Harbor. Since flushing here is poor, it is natural that these subdivisions of the Estuary are characterized by relatively high B.O.D. Even in Northwest and Middle Branches, however, median B.O.D.

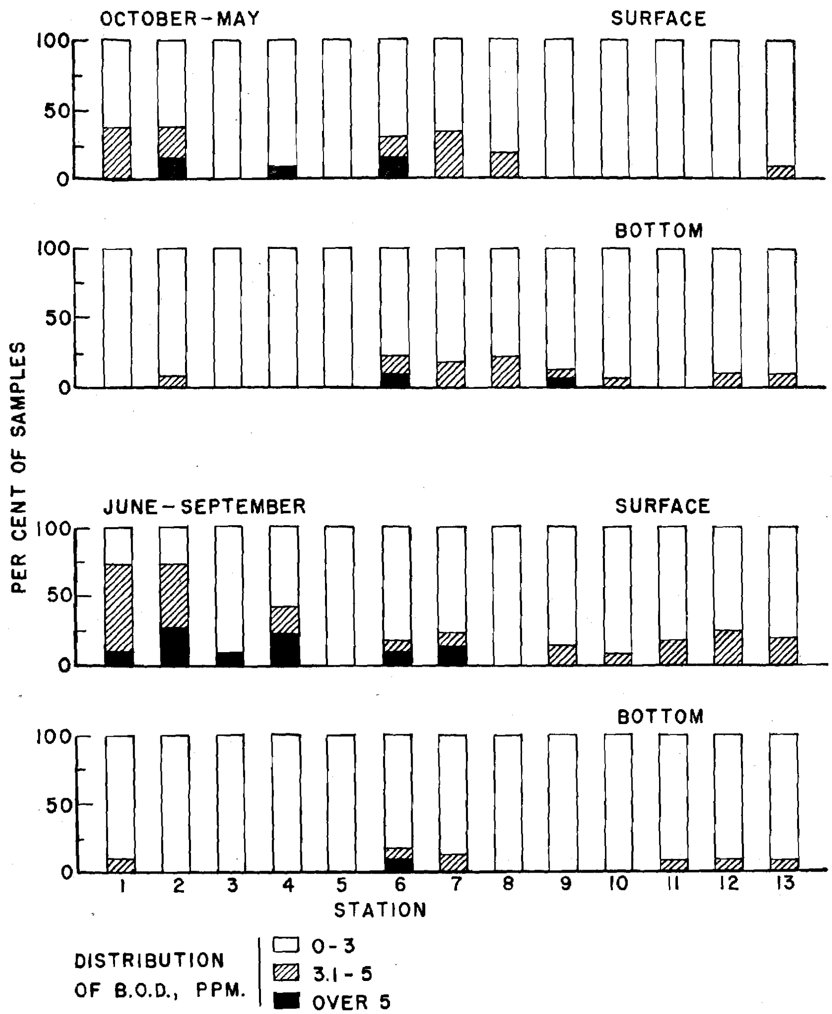


Fig. 18.

Baltimore Harbor

BIOCHEMICAL OXYGEN DEMAND DISTRIBUTION

1947-49

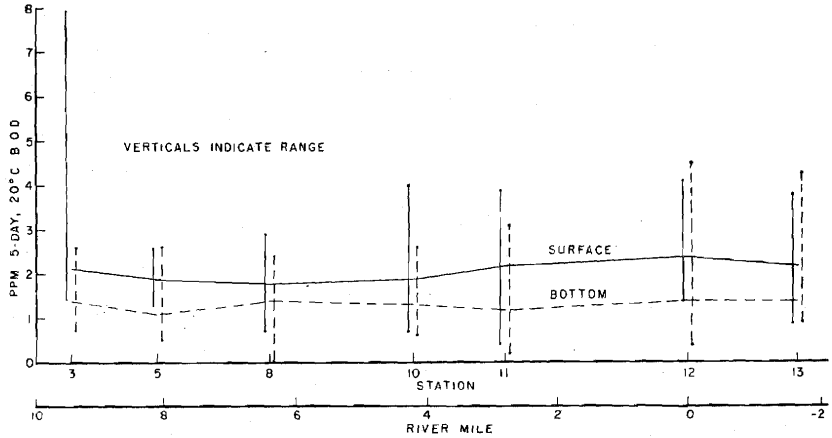


Fig. 19.

Baltimore Harbor

MEDIAN MAIN-CHANNEL SUMMER B.O.D.

1947-49

values during this study were less than 4.0 ppm. and similar values for the remainder of the region were close to 2.0 ppm.

Dissolved Oxygen

The oxygen content of Patapsco Estuary water is characterized fundamentally by a seasonal cycle of subsurface deficits (Fig. 20). Vertical gradients develop with the advent of warm weather and tend to disappear in the fall as water temperatures drop, wind mixing increases and vertical density gradients lessen.

Fig. 21 presents selected data from Appendix G which illustrate a representative sequence of summer events. On March 29, 1949, characteristic cold-season chlorinity and oxygen conditions existed. Vertical oxygen gradients had begun to develop on April 20 and were fully evident on May 18. Prior to July 1, deep mixing modified conditions and produced the homogeneity of that date. Lack of mixing then permitted regeneration of vertical stratification which in turn was destroyed by a heavy storm during the two days prior to August 30. By November 8, water temperatures were down to about 15°C. and vertical oxygen gradients had disappeared.

Examination of oxygen data for the primary fairway (Table 16, Figs. 22 and 23) discloses that during the warm summer months,

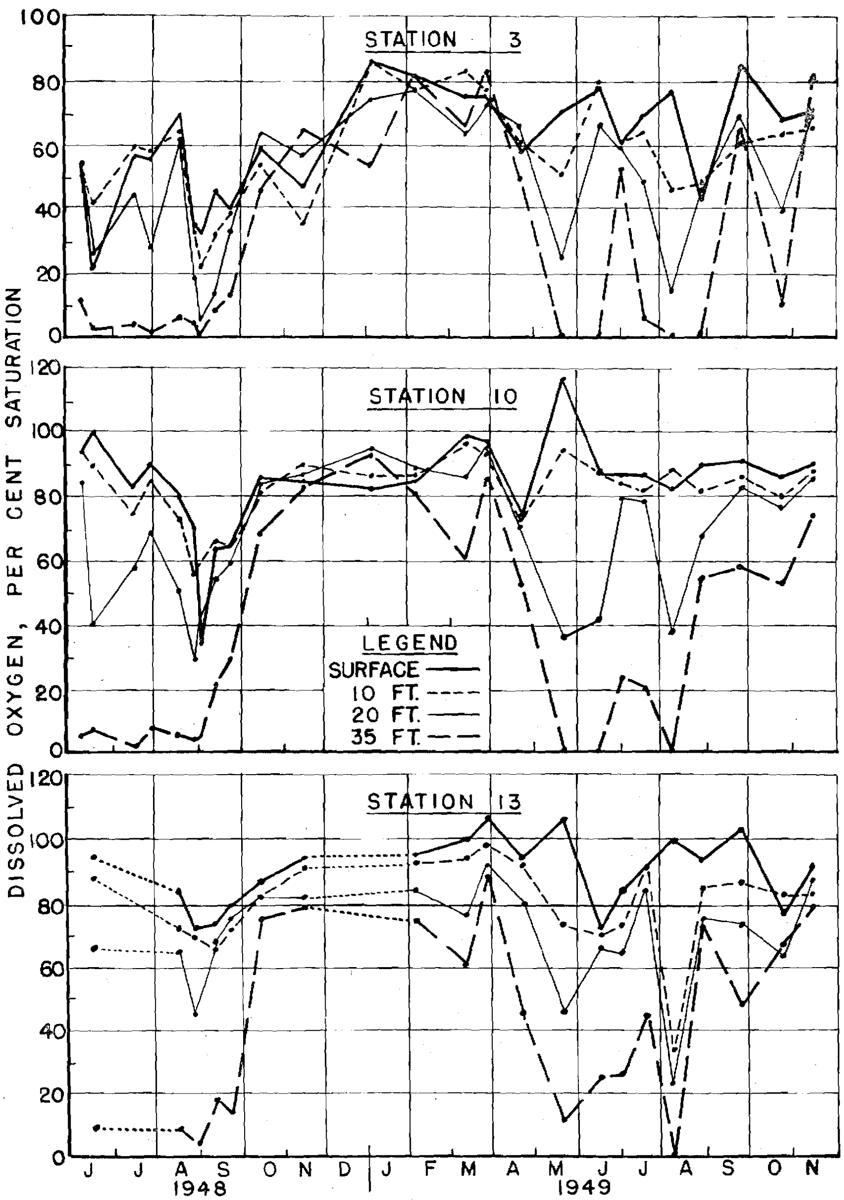


Fig. 20.

Oxygen Variation with Depth, Stations 3, 10 and 13, 1948-49 deficits in water above the undredged bottom averaged only about 25%. The oxygen content of bottom water was virtually nil. For the remainder of the year, vertical gradients were nearly absent and general deficits decreased to perhaps 15%.*

Median D.O. for these regions during cool weather ranges upward from 50% of saturation in Northwest Branch. The oxygen content of Curtis Bay water is lowered as a result of the chemical oxygen demand of industrial wastes.

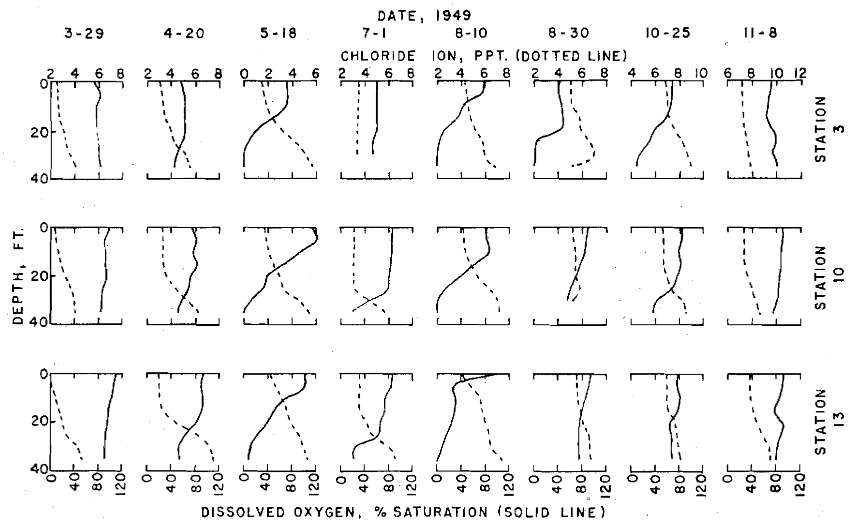


Fig. 21. Baltimore Harbor:

SELECTED CHLORIDE AND OXYGEN VERTICAL GRADIENTS, 1949.

D.O. in the arms of the Estuary was examined in some detail during the summer of 1948. In Northwest and Middle Branches, deficits of virtually 100% for water below the surface resulted from the increased oxygen demand and the inefficient flushing in these areas. D.O. in Colgate Creek was about 50% of saturation. In Bear Creek, surface water was supersaturated while subsurface deficits were negligible except near the steel mill where bottom oxygen was nil. The oxygen content of the upper 10 ft. of water in Curtis Bay and Creek ranged upward from 50% saturation. Deeper water contained little or no oxygen. Judging from concurrent pH and iron determinations, the condition here was a result of bottom accumulation of copperas waste. These findings are probably representative for the warm season.

* Experience indicates that oxygen deficits up to as much as 15% or more may exist in streams free of artificial pollution. This is attributable to natural B.O.D.

TABLE 16

BALTIMORE HARBOR: SEASONAL DISSOLVED OXYGEN

1947-49

*Station***	*Number of Samples*		*Observed D.O., per cent saturation*					
			Maximum		*Median*		*Minimum*	
	*W**	*S**	*W*	*S*	*W*	*S*	*W*	*S*
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1–T	11	15	76	55	53	33	18	15
–B	13	13	67	29	50	7	0	0
2–T	12	12	76	110	66	30	36	16
–B	13	12	73	45	57	7	0	0
3–T	14	18	98	87	72	60	47	25
–B	15	18	84	65	55	6	0	0
4–T	13	13	110	160	83	67	45	20
–B	13	14	97	75	76	42	28	1
5–T	7	9	92	99	87	74	62	38
–B	7	9	77	57	69	3	0	0
6–T	12	12	100	190	81	94	54	13
–B	13	13	84	71	53	9	0	0
7–T	9	12	118	154	79	92	12	37
–B	12	14	91	95	64	5	0	0
8–T	13	13	98	103	84	84	40	48
–B	14	14	89	82	66	12	0	0
9–T	12	14	108	105	84	77	63	51
–B	14	14	90	76	76	60	38	5
10–T	16	15	118	107	84	85	70	35
–B	16	17	89	61	70	11	0	0
11–T	11	11	106	112	93	88	87	66
–B	11	12	93	63	75	6	0	0
12–T	9	12	105	118	99	90	78	78
–B	10	12	92	55	76	12	7	0
13–T	14	14	108	114	94	90	78	72
–B	15	15	94	74	73	18	11	0

* S = summer period, June through September.
W = remainder of year, October through May.
** T = surface; B = bottom.
N.B.: Values for Stations 6, 7, and 9 probabley affected by high concentrations of chemical wastes.

Iron

Total iron was determined on water samples collected routinely to aid in the appraisal of the fate of ferrous sulfate wastes discharged to Colgate Creek, Curtis Bay and Bear Creek.

Water conditions in Curtis Bay have been reported by Olsen,

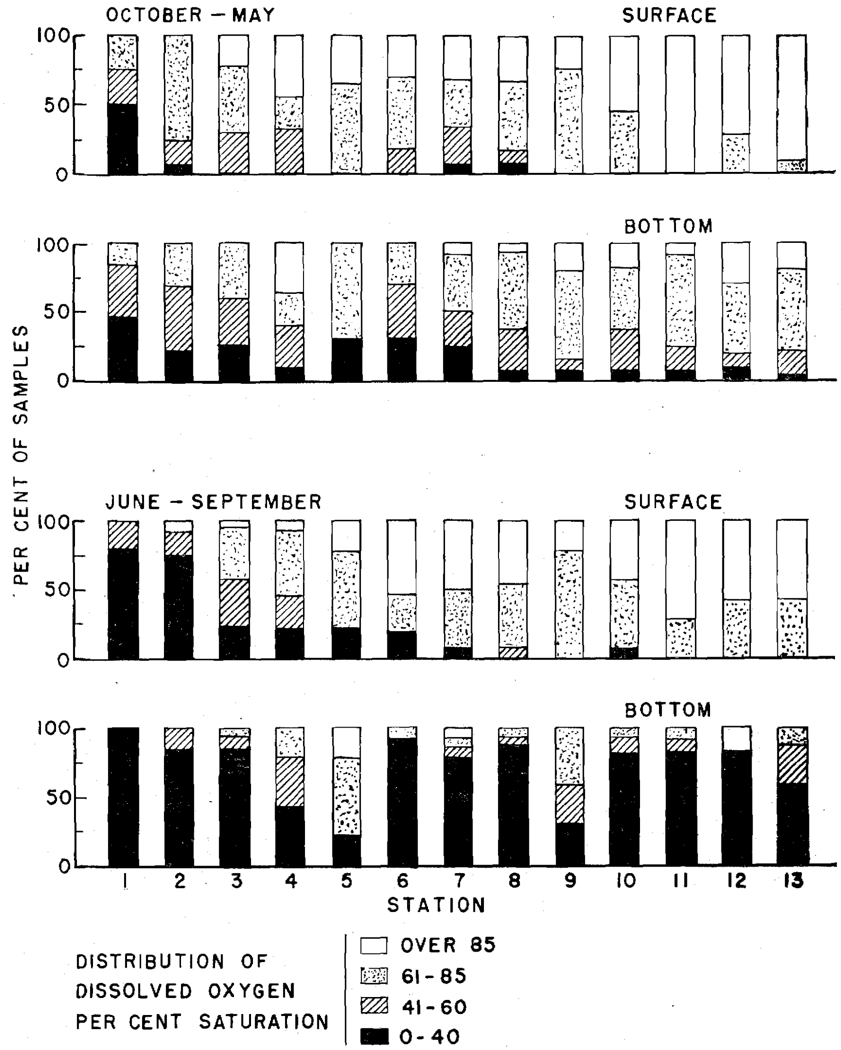


Fig. 22.
Baltimore Harbor
DISSOLVED OXYGEN DISTRIBUTION
1947–49

et al.[20] and Davis.[21] These investigators found that depression of pH and oxygen due to the presence of waste ferrous sulfate was limited to the immediate area. They noted the deleterious effects

[20] Olson, R. A., *et al.*, Studies of the Effects of Industrial Pollution in the Lower Patapsco River Area, I. Curtis Bay Regon, 1941, pub. No. 43, Chesapeake Biological Laboratory, (1941).
[21] Davis, Charles C., Studies of the Effects of Industrial Pollution in the Lower Patapsco River Area, II. The Effect of Copperas Pollution on Plankton, Pub. No. 72, Chesapeake Biological Laboratory, (1948).

of one of the pollutional products, ferric hydroxide, on the ecology of the region and concluded that these effects extended beyond Curtis Bay proper.

Since ferrous sulfate constitutes a large proportion of the total industrial discharges to the Harbor, further discussion of its role as a pollutant is warranted.

The material hydrolyzes to hydrous ferric oxides and sulfuric acid. The ferrous irons produced are oxidized by D.O. in the water to the trivalent ferric state, principally as ferric hydroxide. The solubility product of the latter is extremely small. So at the normal pH of the Estuary, practically all of the iron is present as the insoluble colloidal ferric hydrate. Agglomeration of this material increases it density and it tends to settle out.

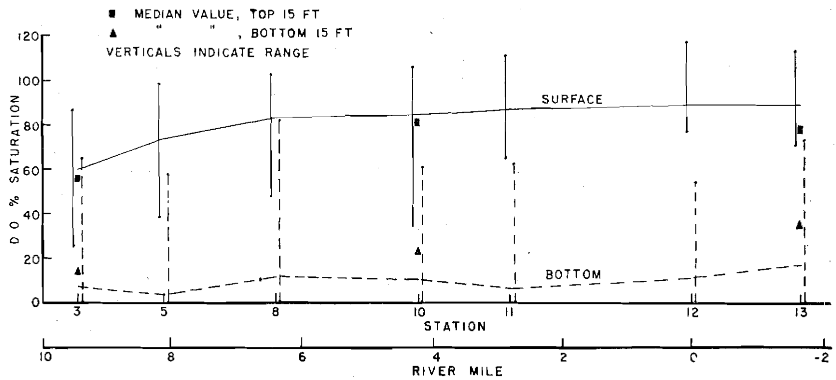


Fig. 23. Baltimore Harbor: MEDIAN MAIN-CHANNEL SUMMER D.O., 1947-49.

A further mechanism which operates when waste ferrous sulfate is discharged to the Harbor has been described by Fair, *et al.*[22] When the ferric hydroxide floc is removed to the bottom it is placed in a reducing environment in which ferric iron is converted back to the much more soluble ferrous form. In this state a portion of it dissolves in the interstitial water of the sediment and is expressed into the supernatant water as consolidation of the deposit procedes. Here it is again oxidized by D.O. to the insoluble trivalent form and the cycle is repeated.

All of the Harbor sections receiving this waste are characterized by indifferent flushing. Accordingly, pollution tends to accumulate in them. During this investigation, iron concentrations in excess of 100 ppm. as Fe were encountered near sewer outfalls. Table 17

[22] Fair, Gordon M., *et al.*, The Natural Purification of River Muds and Pollutional Sediments, Sewage Works Journal, *13*:270 (1941), p. 771.

contains an analysis of observed values by seasons. The distribution of iron concentrations by stations is shown in Fig. 24 and the summer condition of water in the fairway appears as Fig. 25. As found by previous investigators, high iron concentrations did not usually appear far from sources of ferrous sulfate. The iron content of water in the mouth of the Estuary was within the range reported for the Patapsco River above its tidal reach.

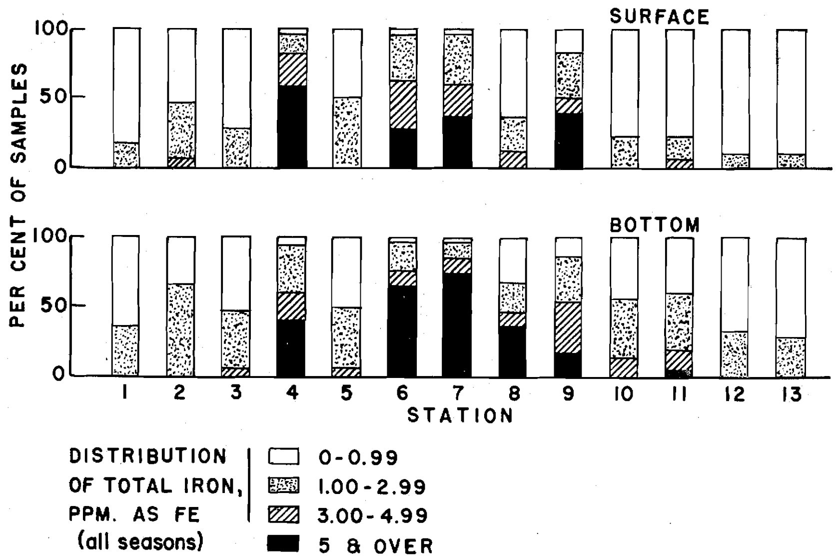


Fig. 24.
Baltimore Harbor
IRON DISTRIBUTION
1947-49

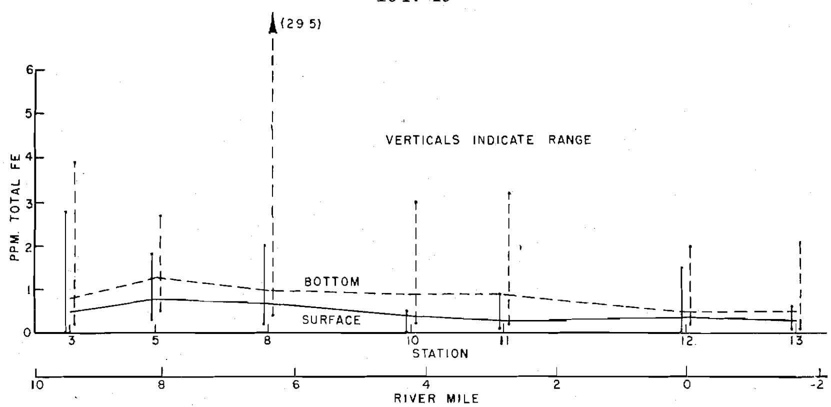


Fig. 25. Baltimore Harbor: MEDIAN MAIN-CHANNEL SUMMER IRON
1947-49

TABLE 17

BALTIMORE HARBOR: IRON CONTENT OF WATER BY SEASONS 1947-49

*Station***	*Number of Samples*		*Observed Total Iron, ppm. as Fe*					
			Maximum		*Median*		*Minimum*	
	*W**	*S**	*W*	*S*	*W*	*S*	*W*	*S*
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1–T	12	12	1.90	1.33	0.71	0.52	0.33	0.18
–B	13	12	2.10	1.23	1.00	0.56	0.40	0.25
2–T	14	12	4.90	2.45	1.75	0.88	0.30	0.33
–B	14	12	2.95	2.45	1.45	1.02	0.30	0.18
3–T	15	14	1.84	2.80	0.92	0.47	0.20	0.00
–B	15	15	3.50	3.86	1.08	0.82	0.15	0.20
4–T	14	13	62.50	46.00	6.70	9.35	0.25	1.20
–B	15	15	140.00	76.50	5.05	2.80	1.40	0.20
5–T	7	9	2.60	1.75	1.33	0.82	0.29	0.28
–B	7	9	3.25	2.71	0.76	1.30	0.54	0.53
6–T	13	12	10.00	11.05	3.62	3.16	0.70	1.25
–B	13	14	36.50	67.60	7.50	9.15	1.60	0.80
7–T	12	13	18.20	9.10	3.44	3.40	1.10	0.70
–B	12	14	44.00	77.20	6.00	11.18	0.70	0.80
8–T	15	13	4.40	2.02	1.00	0.70	0.35	0.15
–B	15	14	27.40	29.50	3.50	0.97	0.50	0.43
9–T	13	15	15.95	10.90	2.90	3.50	0.35	0.30
–B	15	14	15.50	4.70	3.38	1.67	0.47	0.82
10–T	14	12	2.00	0.53	0.45	0.40	0.25	0.02
–B	14	13	8.50	3.00	1.40	0.89	0.25	0.24
11–T	12	11	3.60	0.90	0.40	0.28	0.22	0.12
–B	12	12	5.40	3.22	1.78	0.87	0.40	0.23
12–T	9	12	1.60	1.49	0.37	0.37	0.05	0.00
–B	10	13	2.09	2.03	1.80	0.51	0.37	0.20
13–T	11	10	1.40	0.62	0.29	0.32	0.10	0.07
–B	11	11	2.40	2.12	1.40	0.48	0.38	0.10

* S = summer period, June through September.
W = remainder of year, October through May.
** T = surface; B = bottom.

It appears that subsidence of the iron floc and dilution of the waste during its passage down the Estuary effectively reduce the high iron concentrations found near sources of this particular material. On the other hand, it is likely that some of the floc escapes from the Estuary during storms. Excellent correlation exists between high bottom-water iron and strong winds. In view of the local dominance of winds as a mixing force, the high iron values observed for the cold season are attributed not only to temperature effects, but to the increased water turbulence of these months.

Coliform Bacteria

The limited extent of available coliform data do not warrant an analysis to determine seasonal variations. Most of the data are for warm-weather samples and the results are largely indicative of summer conditions. Table 18 and Figs. 26 and 27 summarize observed data. As would be expected from the distribution of sewage loadings, the principal source of these organisms, coliform bacterial densities were a maximum in the Inner Harbor. Median M.P.N. values here were approximately 16,000 per 100 ml. (milliliters). Fig. 27 discloses that coliform densities decreased exponentially with distance down the Harbor to less than 10 per 100 ml. at the entrance.

TABLE 18

BALTIMORE HARBOR: COLIFORM BACTERIA 1947-49

*Station**	*Number of Samples*	*Observed Coliform Bacteria, M.P.N. per 100 ml.*		
		Maximum	*Median*	*Minimum*
(1)	(2)	(3)	(4)	(5)
1–T	16	1,100,000	17,000	1,400
–B	15	29,000	4,600	210
2–T	16	110,000	15,800	2,300
–B	15	24,000	2,400	140
3–T	17	24,000	3,600	210
–B	15	11,000	930	0
4–T	16	46,000	770	0
–B	14	4,600	130	0
5–T	14	11,000	2,400	140
–B	14	1,500	430	91
6–T	16	9,300	68	0
–B	14	360	18	0
7–T	16	46,000	290	0
–B	14	460	23	0
8–T	16	4,600	840	3.6
–B	15	460	120	0
9–T	16	2,300	260	14
–B	15	1,100	150	14
10–T	16	1,100	150	9.1
–B	15	240	23	3.6
11–T	16	460	33	3.6
–B	14	1,100	23	0
12–T	16	93	9.1	3.6
–B	14	240	6.4	0
13–T	15	41	3.6	0
–B	14	93	6.4	0

* T = surface; B = bottom.

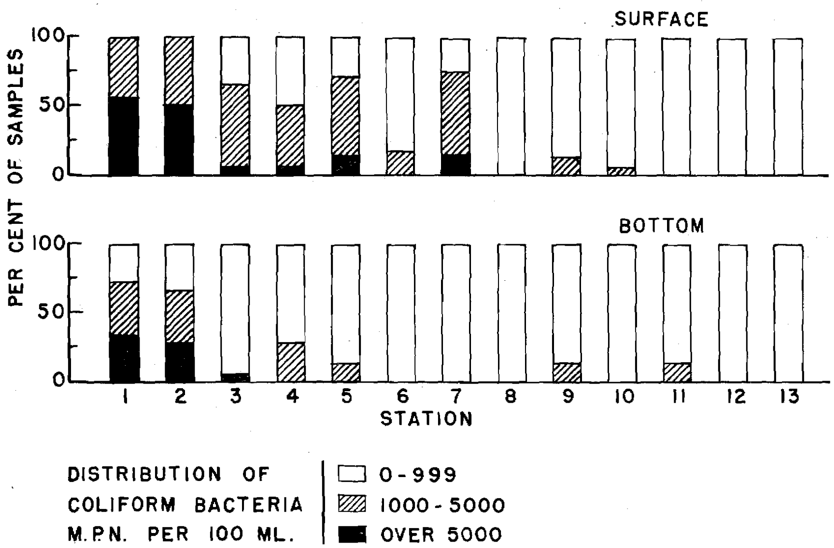


Fig. 26.

Baltimore Harbor

COLIFORM BACTERIA DISTRIBUTION

1947-49

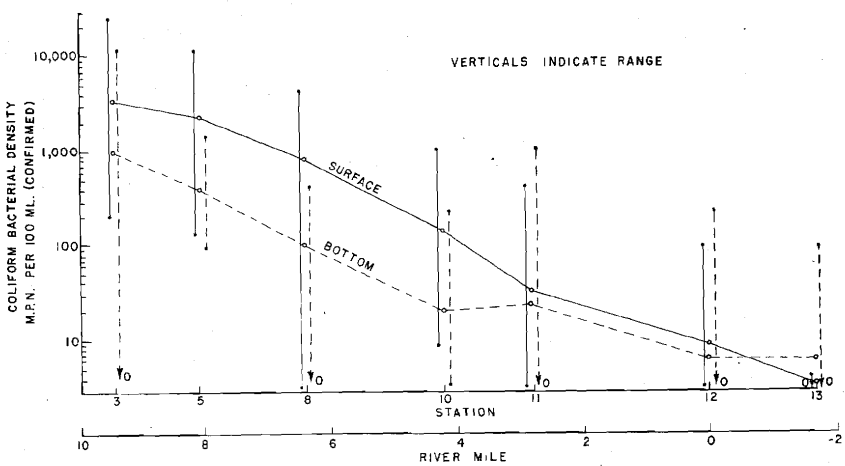


Fig. 27. Baltimore Harbor: MEDIAN MAIN-CHANNEL COLIFORM BACTERIA, 1947-49

Curtis Bay receives, via Furnace Creek, effluent from the small primary sewage treatment works serving the Glen Burnie area. Although coliform M.P.N. values as high as 93,000 per 100 ml. were observed for surface water in Furnace Creek, bacterial densities decreased abruptly below the confluence of Furnace and Marley Creeks as the pH dropped below 5.0.

Bottom Mud

The progressive accumulation of river mud and pollutional sediments in the Harbor has two significant effects: 1) it entails constant maintenance dredging at considerable private and public expense and 2) it modifies the quality of supernatant water. Both of these are considered in subsequent sections of the report.

Character

Nearly 80 mud cores were collected from the Harbor floor during this study. Results of their analysis for total and volatile solids and ether-soluble material (presumably oil and grease) are contained in Appendix F.

The dry solids content of the upper 6 in. of Harbor mud above Sparrows Point averaged about 22%, of which 13% was volatile. The specific gravity of such material is close to 1.13,* hence its specific wet weight is about 71 lb. per cu. ft.

The volatile solids content of Harbor sediment is generalized in Fig. 28. Since results of the standard analysis for volatile material are appreciably affected by local industrial wastes, the information in Fig. 28 requires special interpretation.

Most of the Harbor mud contains considerable deposited iron floc as hydrous oxides of iron which decompose at temperatures less than that of the standard analysis (600°C.). Thus, high volatile solids values do not necessarily indicate the presence of organic pollutional sediments. They may also reveal areas of deposition if iron floc.

Volatile solids constitute up to 10% of the dry solids content of Patapsco River mud above the Baltimore metropolitan area and of bottom sediments from streams in contiguous watersheds. From

* Calculated from assumed specific gravities of 2.5 and 1.0 for fixed and volatile solids, respectively.

$$\text{Specific gravity of wet mud} = \left(\frac{25{,}000}{(250 \times \%\ \text{water}) + \%\ \text{solids}\ (\%\ \text{fixed} + 2.5\%\ \text{volatile})}\right)$$

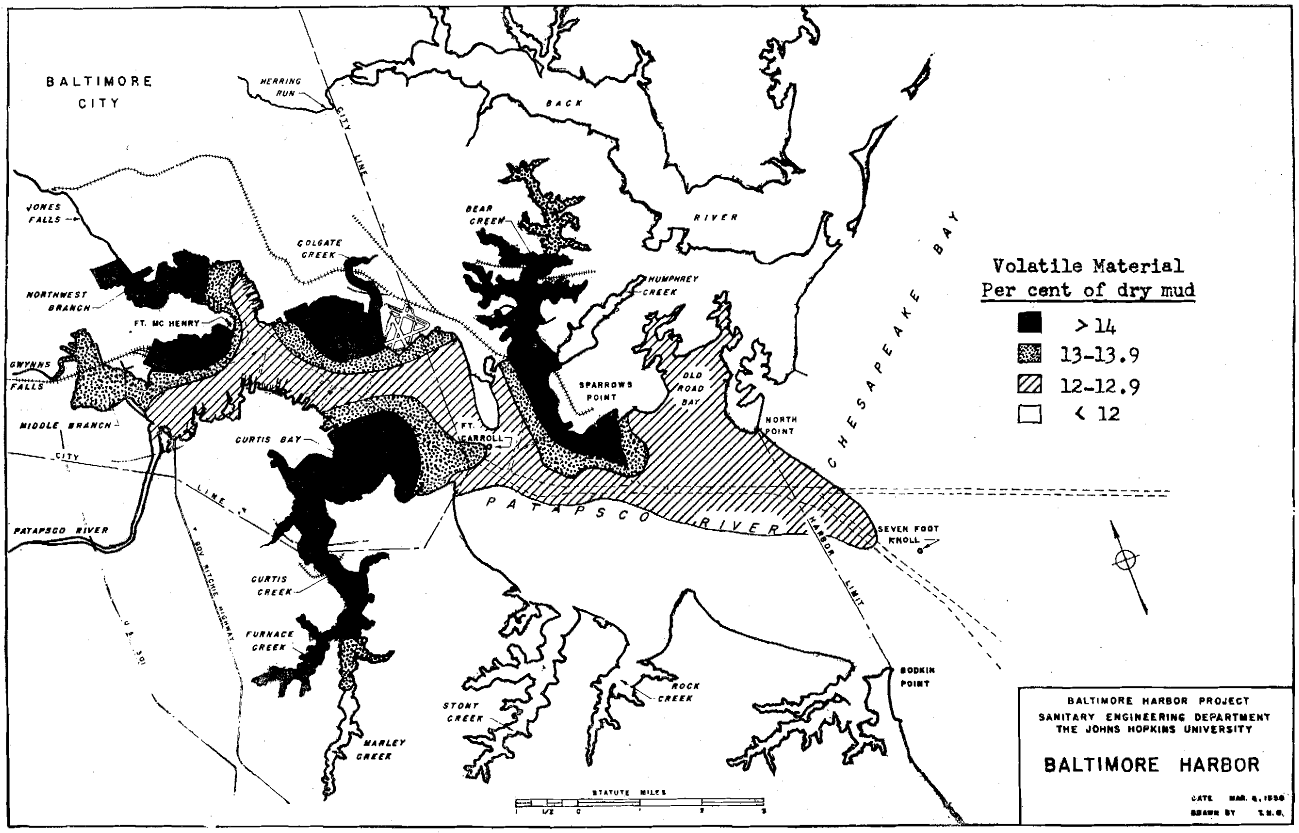


Fig. 28. Baltimore Harbor: VOLATILE SOLIDS CONTENT OF UPPER SIX INCHES OF BOTTOM MUD, 1948-50.

knowledge of the origin and character of Harbor wastes, it may be concluded that the higher values observed for deposits in entrance to the Port reflect the presence of iron floc. In other words, Fig. 28 provides additional evidence that effects of ferrous sulfate discharges are not limited entirely to the Patapsco Estuary.

Fig. 29 shows the distribution of ether-soluble constituents of the mud. Maximum concentrations are close to known shore sources of oil pollution. Unfortunately, mud cores collected in Bear Creek were not analyzed for grease. However, the history of oil pollution in that section makes it likely that mud from the Creek bottom contains a relatively high content of ether-soluble material.

Rate of Accumulation

The flocculating action of sea water upon colloids carried in fresh water is well recognized. It is related to the composition of the colloid and the salinity of the sea water. Most natural clays contain a mixture of replaceable cations which may exchange stoichiometrically with cations in solution (zeolitic or base exchange). A number of studies has shown that such flocculation tends to increase the settling velocity of riverborne silts.[23], [24], [25]

Weiss[26] studied the effect of increasing sea-water concentrations upon settling rates for Patapsco River silt. He noted marked accelerations for chlorinities up to about 5 ppt., beyond which no significant increase occurred.

It is clear from already cited material that the general environment favors flocculation and removal by subsidence of much of the suspended material discharged with wastes or formed by precipitation of waste materials in the Estuary. However, examination of Harbor hydrographic charts for the last century discloses no significant shoaling outside of the dredged areas. It appears, then, that most of the material deposited in shallow areas is swept to the channels by storm-induced currents and is being removed by private and public dredging.

The City Bureau of Harbors and the Army Engineers have recorded all dredging within the Estuary. In using these records it is difficult to separate new work from maintenance operations. How-

[23] Sverdrup, H. U., *et al.*, The Oceans, Prentice Hall, New York (1946) pp. 958, 988.
[24] British Water Pollution Research Board, Estuary of the River Mersey, Water Pollution Research Tech. Paper No. 7 (1938), p. 91.
[25] 1914 Annual Report, Metropolitan Sewerage Commission of New York, p. 617.
[26] Weiss, C. M., Removal of *Escherichia coli* from Estuarine Waters by Absorption on and Flocculation of Silts, doctorate dissertation, Johns Hopkins University (1950), p. 16.

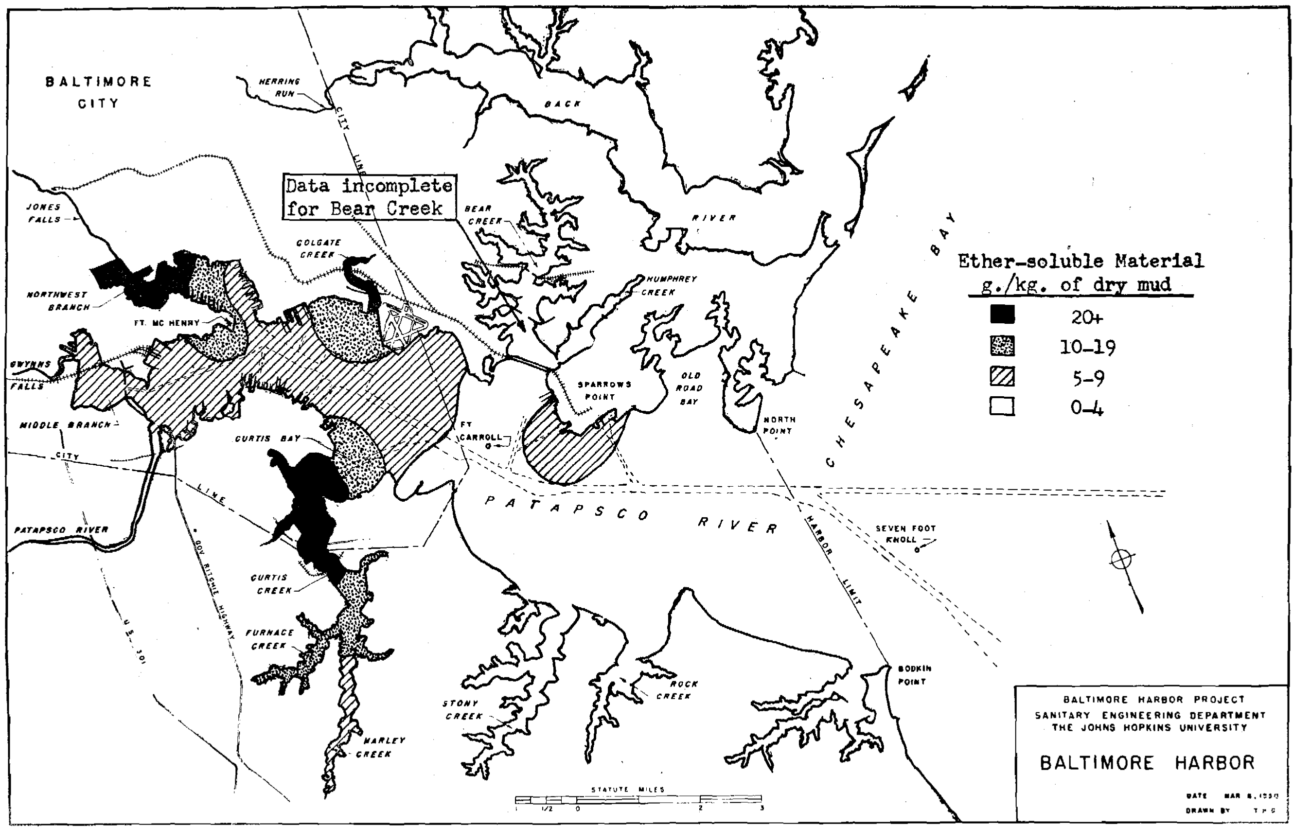


Fig. 29. Baltimore Harbor: ETHER-SOLUBLE MATERIAL IN UPPER SIX INCHES OF BOTTOM MUD, 1948 50.

ever, an annual figure of 1,000,000 cu. yds., scow measure, appears to be a reasonable estimate of the latter. This is approximately equivalent to 750,000 cu. yds. per year *in situ*.*

Information is lacking as to the silt load of the Patapsco in the absence of artificial pollution (but including upland soil erosion). Without measurement, recourse must be made to estimates based on experience elsewhere. U. S. Soil Conservation Service data for the Southern Piedmont region indicate a median siltation rate of 0.44 acre-ft. per sq. mi. annually for fresh-water streams as large as the Patapsco.[27] This is equivalent to an annual accumulation of 435,000 cu. yd.

Sediment surveys of Baltimore City's raw-water reservoirs on a watershed adjacent to that of the Patapsco disclosed a rate of sediment production considerably above the average for the Southern Piedmont. This, together with the more flocculent nature of marine muds in general, seems to point to a figure greater than the above estimate for "normal" harbor siltation. A sediment load of 750,000 cu. yd. per year from the Patapsco is a specific rate of 0.76 acre-ft. per sq. mi. per yr., which falls within the observed range for comparable Southern Piedmont watersheds—0.27 to 0.80 acre-ft. per sq. mi. per yr. Considering the influence of such added factors as the sloughing of channel shoulders, the entrance of material from the Bay and the flocculation of colloids, it seems reasonable to conclude that pollutional sediments are a small fraction of the total siltation within the Patapsco Estuary.

While the extent to which dredging costs are increased by deposition of suspended solids from municipal and industrial wastes cannot be estimated accurately, the increment, whatever its magnitude, undoubtedly represents a small portion of the total cost of channel maintenance.

Distribution

Information on maintenance dredging for the Harbor proper indicates that material accumulates within principal channels at a rate of 400 cu. yd. per acre annually, with surprisingly little variation over the Estuary. Outside the Port, rates of deposition of sediment in the channel range up to more than twice this amount and are be-

* The U. S. Soil Conservation Service has suggested 600,000 cu. yds. annually as a "conservative" estimate of Baltimore Harbor siltation. Cf. Gottschalk, L. C., Sedimentation in a Great Harbor, Soil Conservation, Vol. X, No. 1 (July, 1944).

27 Brown, Carl B., discussion of paper by Bernard J. Witzig, Sedimentation in Reservoirs, Trans., Am. Soc. of Civil Engrs., *109*:1047 (1944), p. 1084.

lieved to reflect a trapping of solids drifting along the west shore of the Bay rather than any precipitous unloading of solids from the Harbor effluent.

Summary

Review of analytic data for water and bottom mud collected from Baltimore Harbor during the period August, 1947, through March, 1950, discloses that discharge of domestic sewage and industrial wastes to the Patapsco Estuary has produced the chemical, physical and bacterial pollutional effects indicated below.

Chemical Pollution

Discharge of chemical wastes to Colgate Creek, Curtis Bay and Bear Creek has significantly reduced pH in these sections. Water is generally acid and free acidities of as much as several hundred ppm. as $CaCO_3$ are not uncommon. Colgate Creek is affected in its entirety. Effects of discharges to Curtis Bay extend westward to the head of navigation in both Furance and Marley Creeks and eastward into the main fairway. pH and acidity effects in Bear Creek are less severe and are limited to the vicinity of Sparrows Point.

Appreciable oxygen deficits ascribable to artificial pollution are limited largely to innermost sections of the Harbor and to summer months. During warm weather, the oxygen content of water in Middle and Northwest Branches and of deep water in the main fairway is virtually nil. The D.O. of water in Colgate Creek, Curtis Bay and in the mouth of Bear Creek is lowered to some extent by chemical wastes. Deficits at other locations result primarily from natural and artificial organic waste loadings. The degree to which artificial pollution is responsible for these conditions is not entirely clear.

The iron content of water in the vicinity of waste ferrous sulfate discharges is increased markedly. Harbor water would contain normally not more than about 2 ppm. of iron as Fe. Average concentrations near sources of iron-bearing waste in Curtis Bay, Colgate Creek and Bear Creek approach 10 ppm. and peak values may exceed 100 ppm. Dilution and neutralization of the wastes in the alkaline waters of the fairway, together with subsidence of the insoluble colloidal iron compounds formed after discharge, commonly reduce the iron content of most of the water in the main portion of the Estuary to very nearly normal values. Available evidence, however, indicates escape of some of the colloidal iron from the Harbor during storms and in the winter season when water turbulence is greatest and temperatures lowest.

Physical Pollution

Oil pollution, a constant source of difficulties in the Port, produces unpleasant grease balls and slicks. Near on-shore origins, some of this material breaks up and is carried to the bottom where, with other settleable organic debris, its biochemical stabilization augments oxygen requirements. A portion of it creates a fire hazard by accumulating on timber water-front structures.

It appears that most of the hydrous iron oxides formed after discharge of waste ferrous sulfate accumulate within the Estuary as bottom sludge. No evidence was found, however, that pollutional sediments comprise more than a small fraction of the total volume of silt unloaded in the Estuary by its tributary streams.

Water in Colgate Creek, Curtis Bay and Bear Creek is customarily colored brown or deep green by the waste ferrous sulfate discharges originating here. Between Wagners and Sparrows Points, water in the main fairway usually exhibits a muddy brown color due to its content of precipitated iron. Depths of light penetration and the ecology of the region are modified by this artificial turbidity.

Bacterial Pollution

Sewage discharges to the Estuary produce median M.P.N. values for coliform bacteria ranging from 16,000 per 100 ml. in the Inner Harbor to less than 10 per 100 ml. at the Harbor entrance. Surface water contains greater numbers of these organisms than does the more saline water near the bottom. There is evidence that high acidities in Curtis Bay are bactericidal.

SECTION VI.

DISCUSSION

Preceding sections of the report present information relative to the origin and character of pollutional discharges to the Patapsco Estuary, the hydrography of the region, and the present sanitary status of water in the Harbor basin. In the discussion which follows, these findings are interpreted further in terms of their joint relationship to water quality in Baltimore Harbor. First, in view of the importance of maintaining adequate oxygen levels within the Port, the oxygen economy of the Estuary is examined. Second, the function of the Harbor Basin as a waste treatment unit is developed. Third, the suitability of the Harbor water for present and probable future uses is considered. In addition, the outlook for the future is discussed.

THE OXYGEN BALANCE

When organic wastes are discharged to a stream, the flora and fauna of the watercourse multiply rapidly; oxygen demand is correspondingly stimulated and stream D.O. is lowered. If this demand is exerted at a rate which is greater than that at which oxygen is supplied, total depletion of oxygen may result.

Stream self-purification proceeds anaerobically as well as aerobically. Stabilization of organic materials in the absence of oxygen, however, is relatively protracted and results in formation of malodorous and toxic intermediate compounds which may create a nuisance. It is desirable to maintain an aerobic environment with its normal complement of aquatic life, pleasing appearance and lack of odor. Consequently, D.O. is a widely utilized diagnostic index of the sanitary status of surface waters.

For inland streams where flow is essentially unidirectional, the D.O. profile below a source of reasonably constant pollution assumes a characteristic shape which is referred to as "the oxygen sag." The sag curve reflects the equilibrium between reoxygenation and deoxygenation processes. It has been formulated mathematically and may be predicted under certain conditions.

While it would be useful to be able to apply such an analysis to Harbor oxygen conditions so as to enable prediction of D.O. under modified pollution loads, present knowledge of dilution and water exchange for the Estuary make such procedure impracticable. Approximate analysis of components of the local oxygen balance is feasible, however, and aids in explaining observed conditions, as well as in disclosing the general capability of the Harbor for aerobic stabilization of organic wastes.

The nature of local oxygen resources and demands is noted below.

(1) **Oxygen Resources**

a. D.O. in waste discharges themselves.

b. D.O. in the water of the receiving stream or subsequent dilution thereof.

c. D.O. acquired through reaeration or solution of atmospheric oxygen.

d. Oxygen given off during the photosynthetic activity of certain aquatic plants.

(2) **Oxygen Demands**

a. B.O.D. of organic pollutants.

b. Bottom-mud or benthal demands.

c. Natural B.O.D. of the receiving stream itself.

d. Chemical oxygen demand of pollutants.

Each of these has been evaluated by methods set forth in Appendix D. It suffices here to list the principal findings for warm-weather conditions—the critical period.

*RESOURCE CATEGORY**	*Oxygen lb. per day*
a. D.O. of wastes	negligible
b. D.O. in new dilution water	150,000
c. Reaeration	185,000
d. Photosynthesis	400,000
TOTAL	735,000
*DEMAND CATEGORY**	
a. Ultimate B.O.D. of wastes	100,000
b. Benthal requirements	170,000
c. Natural B.O.D. of receiving water	420,000
d. Chemical oxygen demand of industrial wastes	20,000
TOTAL	710,000

* Resource category (c) assumes maintenance of a 25 per cent oxygen saturation deficit and (d) assumes that one-third of the total production is lost to the atmosphere. Demand category (b) involves the assumption that summer demands are twice the mean daily requirement; (c) comes from an assumed 5-day 20°C. value of 1 ppm. corrected to a temperature of 25°C. by means of the fundamental B.O.D. equation and a velocity constant of 0.12.

The uncertainty of basic data and the state of knowledge regarding operation of certain of the balance mechanisms make further refinement of the analysis unwarranted.

At present Harbor oxygen saturation levels the role of reaeration is limited. However, a further general lowering of D.O. would bring into play the appreciable reaeration potential of the Estuary. Summer reaeration at 50% and 25% D.O. saturation would be about 375,000 and 560,000 lb. per day, respectively. It thus appears that the Estuary is capable of assimilating much greater organic loadings than now obtain. In this connection, the distribution of loading is of fundamental importance. Existing disproportionalities within the Upper Harbor have overbalanced local assimilative capacities and produced the marked oxygen deficits observed in innermost sections.

While at first thought it may appear reasonable to impute observed Harbor oxygen conditions entirely to pollution, previous field studies have demonstrated analogous summer conditions in the entire nothern half of Chesapeake Bay remote from sources of artificial pollution.[28, 29] The characteristic is sufficiently general to warrant special attention. Summer oxygen deficits in the bottom portion of Baltimore Harbor channels, while doubtless intensified by local waste discharges, are believed to reflect a fundamental phenomenon involving the entire Chesapeake Bay. The net flow of bottom water in the Bay and in tidal reaches of its tributaries is upstream. As this relatively dense oceanic water moves inward, its oxygen content is drawn upon for satisfaction of bottom-mud demands which are considerably augmented during the warm season.

Oxygen can enter bottom strata only by slow diffusion or inward transport (mixing) of aerated fresher water from above. But the topography of the region makes both of these processes relatively inefficient. On the basis of the direction of net flow, it would be expected that summer oxygen deficits for bottom water would increase progressively toward the head of the Bay. Field observations show that this is the case. Bottom deficits first appear in the Upper Bay in April or May. As oxygen saturation values here decrease through the warm season, the southward extension of deficits becomes greater. With the advent of the cool fall season, a lessening

[28] Newcombe, Curtis L. *et al.*, Studies on the Physics and Chemistry of Estuarine Waters in Chesapeake Bay, Journal of Marine Research, Vol. II, No. 2, pp. 87-116 (1939).
[29] Chesapeake Bay Institute, Report No. 1, Cruises I and II (1949).

and retraction of Upper Bay deficits becomes apparent, until they disappear—usually by November.

It is likely then that the warm-weather oxygen deficits observed in the lower depths of the Patapsco Estuary are an aggravation of a natural tendency. The rather isolated artificial basin comprising the lower portion of dredged channels and anchorages generally contains water of relatively high density (salinity). During the warm summer months, D.O. here is nil. However, since the affected volume is less than one-fifth of the total contents of the Harbor, the condition has little sanitary significance. As this bottom water mixes upward, its oxygen deficits are rapidly overcome by dilution, reaeration and photosynthesis in the overlying stratum.

The Patapsco Estuary As A Waste Disposal Mechanism

Baltimore Harbor is used extensively as the receiving stream for enormous quantities of domestic and industrial wastes. Fndings of this investigation disclose that domestic sewage B.O.D. loading is equivalent to that which would result from the discharge of untreated sewage from nearly 100,000 persons. Manufacturing establishments, principally chemical and metallurgical, discharge more than 700 tons of solids to the Port each day. The fact that water conditions, except in the innermost sections, are not particularly degraded is direct evidence of the huge natural assimilative capacities possessed by the Estuary.

Economic Values

Use of at least a portion of the natural Harbor capacities for assimilating wastes has certain obvious economic value. Brief consideration of some of the savings inherent in the present situation will emphasize this point. It is estimated, for example, that during the warm season the Harbor is daily providing upwards of 750,000 lb. of oxygen for the aerobic stabilization of wastes and pollutional sediments. The local cost of furnishing this weight of oxygen in conventional waste treatment works would be in excess of $3,000 per day for power alone. The basis of this estimate is as follows: The oxygen content of air is about 17 lb./1,000 cu. ft. During 1949, power costs for air compression at Baltimore City's Back River Sewage Treatment Works amounted to $5.85/million cu. ft. Assuming an absorption efficiency of 8 percent, the daily cost of providing 750,000 pounds of oxygen in the aeration units would be

$$\frac{750{,}000 \times 5.85}{0.017 \times 0.08 \times 10^{6}} = 3{,}230 \text{ dollars/day.}$$

A further value susceptible to direct appraisal is the natural neutralization of acidic industrial wastes. Some 220 tons of acidity as equivalent sulfuric acid reach the Estuary each day in industrial effluents. An additional 260 tons per day of this acid are produced by hydrolysis of the 400 tons of waste ferrous sulfate discharged daily. The total acid neutralized each day by the natural alkalinity of the Harbor water must be the equivalent of at least 480 tons of sulfuric acid. The actual amount is doubtless higher. On the basis of hydrated lime at $11 per ton, the value to industry of this neutralization approaches $4,000 per day for the neutralizing agent alone.

Fate of Wastes Reaching the Estuary

In view of the multiplicity of chemical, biological and physical processes operating within the Harbor, reliable *a priori* quantitative evaluation of the fate of pollutants is impracticable. It has been noted that the Estuary affords an environemnt which highly favors removal of suspended and dissolved substances. Precipitation, coagulation and sedimentation processes are promoted by the salinity and slow movement of the Harbor water. Furthermore, these natural tendencies are enhanced materially at present by the discharge of waste ferrous sulfate which acts as a coagulant.

It is impracticable to attempt to predict from theoretical considerations the extent to which waste constituents will precipitate after discharge. In general, dissolved salts will come out of solution of their ionic product exceeds their solubility product. However, because of the complex nature of sea water, relatively little is known of the solubility products of substances in seawater dilutions. Studies have indicated over a thousandfold increase in the apparent solubility product of certain salts relative to comparable distilled-water values.[30] In the absence of adequate technical information, the extent to which specific pollutants will precipitate after discharge only can be determined empirically.

The adsorptive power of Patapsco River silt is also effective in removal of suspended and dissolved substances. Weiss[31] experi-

[30] Sverdrup, H. U., *et. al.*, The Oceans, Prentice-Hall, New York (1946), p. 210.
[31] Weiss, C. M., The Removal of *Escherichia coli* from Estuarine Waters by Adsorption on and Flocculation of Silts, doctorate dissertation, The Johns Hopkins University (1950), p. 39.

mentally demonstrated the mechanism in connection with the re-removal of bacterial cells. This investigation also showed that the adsorptive capacity of the silt was reduced in a saline environment such as obtains in the Estuary. So the importance of this mechanism in removal of Harbor pollutants is uncertain. Dissolved organic substances are dissimilated biochemically to relatively inert compounds which eventually reach Chesapeake Bay. Inorganic materials which are not precipitated and settled to the Harbor bottom are dissipated ultimately by dilution in the Bay.

Effect of Harbor Pollutants on Chesapeake Bay

The water-quality data of this study show that under present waste loadings, the multiple processes operative within the Harbor proper are able to effect virtual recovery of natural quality as the water moves downstream to Chesapeake Bay. The quality of Harbor water at the entrance to the Port off North Point indicates that no significant modification of Chesapeake Bay water occurs as a result of waste discharges in the Patapsco Estuary. This conclusion is based on the particular diagnostic indices used in this investigation. It is conceivable that the ecology of the Bay might be affected by the addition of small concentrations of unidentified chemicals discharged in industrial wastes. The available dilution is so great, however, that such possibility is indeed remote.

The dry-weather flow of the Susquehanna River is about 13,000 mgd. This volume of water is available for dilution of Patapsco River discharge with its contained pollution. Dilution is augmented further by the addition of saline bottom water moving up the Bay in an amount necessary to maintain the salinity of 8,000 ppm. which exists off the Harbor during dry weather. Disregarding the salt water, more than 50 tons per day of the substance derived from wastes would have to pass out of the Harbor in order to produce a concentration of 1 ppm. in the Bay after dilution.

Limitation of Use for Waste Disposal

The distribution of waste discharges is a primary consideration in the use of the Estuary as a receiving stream. Tremendous natural abilities for waste assimilation are available. But they can only be realized when pollutants are effectively dispersed throughout the Harbor. Failure to accomplish this accounts for present degraded conditions in certain areas.

The Harbor basin functions effectively as a natural sedimentation unit affording a lengthy detention period for wastes which are discharged to it above Sparrows Point. Under these conditions, the sludge potential of organic wastes is a primary consideration. Accumulation of quantities of decomposable pollutional sediments is certain to create severe bottom-mud demands.

Suitability of Harbor Water For Uses Other Than Waste Disposal

While waste disposal constitutes a legitimate stream use, it should not be permitted to affect adversely other higher-priority stream functions. In the absence of such preferential uses, treatment of domestic and industrial wastes is generally directed toward avoidance of a public nuisance. In other words, under these conditions the maximum practicable use is ordinarily made of natural stream self-purification capacities. The Harbor has primary functions other than serving as a repository for wastes. There is need, therefore, to appraise the degree to which navigation, cooling water supply and the limited use for recreation are affected by present waste disposal practices.

To expedite the discussion there is summarized in Table 19 a set of water-quality specifications believed to be reasonable for Harbor water uses other than waste disposal. Such criteria represent experience with reference to the suitability of the Harbor water for various uses. They serve as flexible guides to judgment. Comparison of the existing water conditions in the Estuary with such criteria affords a means of evaluating the extent to which the different uses may be adversely affected.

Navigation

Acid discharges impair the suitability of salt water for navigation by intensifying its corrosive characteristics. Such an effect results from the dumping of waste acids and acidic materials from industries. Occasionally, gross domestic sewage pollution interferes with shipping by producing obnoxious water conditions and sludge banks.

The available evidence indicates that the last mentioned conditions are not a problem in Baltimore Harbor. Industrial waste discharges in Curtis Bay and Creek, in Colgate Creek and in Bear Creek, however, have adversely lowered the pH of water in these

TABLE 19

QUALITY SPECIFICATIONS FOR VARIOUS WATER USES IN BALTIMORE HARBOR

Characteristic	*Monthly Occurrence*	*Navigation*	*Industrial Cooling*	*Recreation*	
				Bathing, boating and fishing	*Aesthetic Enjoyment*
(1)	(2)	(3)	(4)	(5)	(6)
1. Coliform bacteria, M.P.N. per 100 ml.	median maximum	....	25,000 100,000	2,400 10,000	....
2. Dissolved oxygen, per cent saturation	median minimum	25 10	25 10	60 40	25 10
3. pH value	range	5 to 9	5 to 9	6.5 to 8.5	....
4. 5-day, 20°C., B.O.D., ppm.	median maximum	3 10	3 10	3 5	....
5. Oil	(*)	occasional	none	none	none
6. Slude deposits	(*)	—moderate, general—		—no preventable—	
7. Surface debris	(*)	no preventable			
8. Other	(*)	no high temperature or obnoxious odor		no noticeable taste or odor, toxic substances, objectionable color, temperature of turbidity.	

(*) Limiting requirement for desirable use.

sections. Commercial navigation in Colgate and Bear Creeks is limited. Curtis Bay is the principal area where pollution effects shipping and related physical facilities.

Industrial Cooling

Industrial cooling systems in Harbor manufacturing establishments are, for the most part, the single-pass type. Water is pumped from the Estuary through a closed cooling system and returned without cycling. Here again, corrosion is the chief concern. In addition, the presence of organic wastes sometimes reduces heat-exchange efficiency by stimulating the growth of slimes within the system.

Several Curtis Bay plants neutralize the acid water of this region before use. The cost of such treatment, together with the decreased life of cooling systems in this section, is economic damage directly attributable to stream pollution. Colgate Creek water fails to meet the desirable specifications for use in cooling systems. The single industrial plant which takes water for cooling from this section of the Harbor is itself responsible for local acidities. Acidities in the mouth of Bear Creek make the water undesirable for cooling uses. As far as determined, however, there is no such use in this area. Slime control does not appear to be a significant difficulty. A few power plants that are large users of Inner Harbor water for cooling control slimes by chlorination.

Recreational and Aesthetic Values

While it is true that the recreational and aesthetic values of the Harbor to the citizens of the metropolitan area are limited by commercial development of the waterfront, such values are present. Inclusion of a new downtown waterfront park in the current port development program and the increased residential and recreational use of the water and shores of the Lower Harbor are witness to this. The advisability of some of these uses is perhaps questionable. Their development results from a desire to take advantage of inherent esthetic values as well as from the human propensity for aquatic recreation.

Except in the entrance to the Estuary at the Bay, Harbor conditions are unsuited to recreational use. Bathing and swimming above Sparrows Point are hazardous, according to currently accepted bacterial standards. Actually, the unpleasant physical condition of Inner Harbor water is effective in deterring such use, as well as in dampening any general enthusiasm for boating and fishing. In addition to the frequent presence of slicks and trash, water here is often made "dirty" in appearance by silt carried into the Harbor during storm runoff from the fresh-water streams draining through the Estuary. A similar discoloration is produced by waste iron sulfate from industry. Noticeable odor or other offensive evidence of pollution detract from the aesthetic value of a body of water. Oil discharges are especially objectionable and have caused trouble in nearly every section of the Port at one time or other. The Inner Harbor functions effectively as a trap for wind-driven surface debris and oil.

Fishing and crabbing within the Estuary, practiced once upon a time by local residents, have virtually come to a stop, a change that undoubtedly resulted from waste discharges.

WATER-QUALITY TRENDS AND FUTURE CONDITIONS

This report, for the most part, has dealt with present Harbor conditions. What is the outlook for the future? In this connection, it is instructive to examine the trend of water quality in the Estuary as disclosed by the somewhat meager historical data available.

Water-quality Trends

Although the usefulness of the City's harbor sampling program is limited, the resulting data go back to 1929 and afford the best available indication of trends. The record for surface-water pH at four locations within the Upper Harbor is indicated in Fig. 30. A general downward trend is evident. Daily pH records since 1940 are available for three Curtis Bay locations. In Table 20 there is presented an analysis of summer data for selected years for surface water at the Pennington Avenue bridge just above Station 6. Water at that point has become increasingly acid during the past decade. The percentage of time that the pH was 5.0 or less increased abruptly during World War II from 4% to 50%. Since the War further degradation has occurred.

The limited data on oxygen conditions reported for the year 1906 by the Baltimore Sewerage Commission do not provide as adequate a basis for a comparison of present and past conditions as might be desired. The oxygen content of surface, mid-depth and bottom water at 13 Harbor locations was recorded by the Commis-

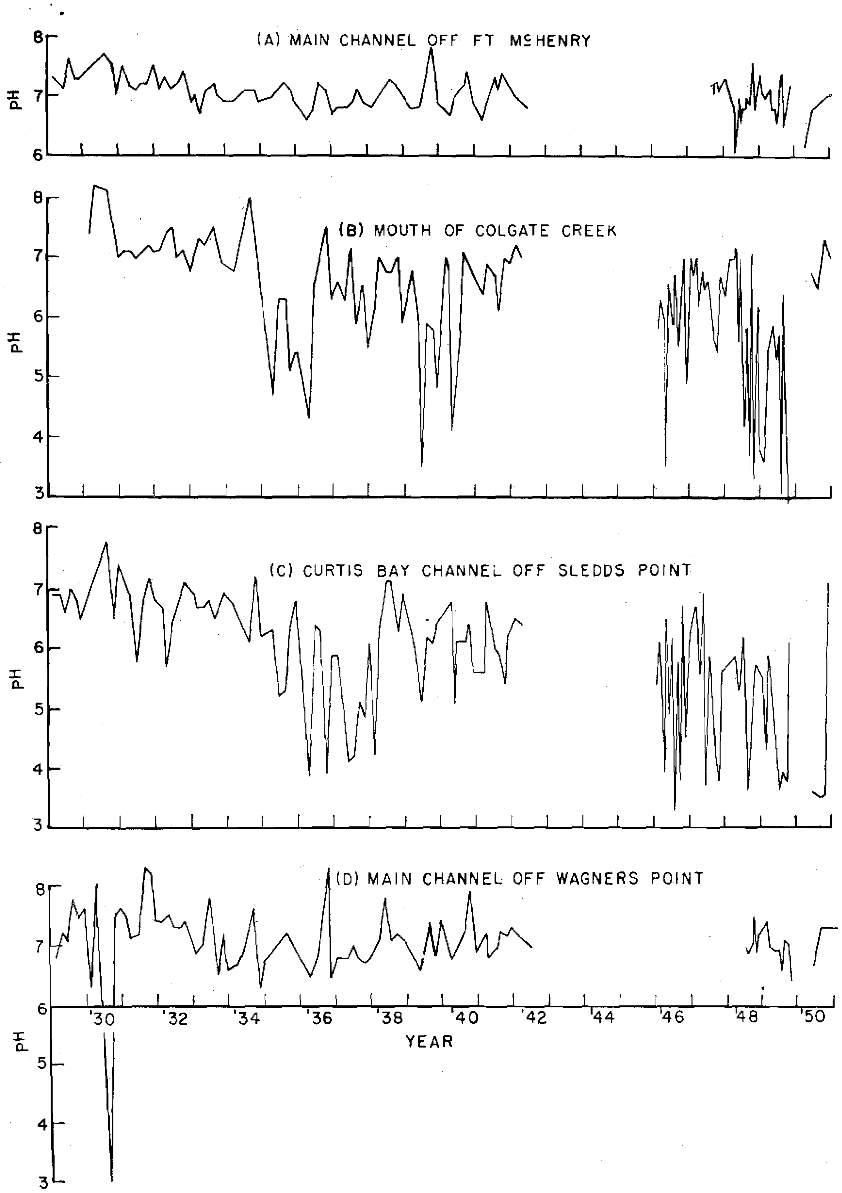


Fig. 30.

Baltimore Harbor
HISTORY OF SURFACE-WATER pH
AT FOUR UPPER HARBOR LOCATIONS
(Data 1929-42 and 1950, City Bureau of Sewers, other, Baltimore Harbor Project, Johns Hopkins University.)

sion. But the single set of samples analyzed was collected during April and May when the critical conditions of warmer weather had not developed. However, a comparison of this information with current findings for the same time of year indicates a subsequent deterioration of water quality in the amouth of Bear Creek, in Curtis Bay and in the fairway off Ft. McHenry. Improvement is evident in Northwest and Middle Branches. In the light of changes known to have occurred since 1906, these trends are as expected. The Bureau of Sewers' oxygen data for surface water at four selected Upper Harbor locations, Fig. 31, show increasing deficits for the period of record.

TABLE 20

BALTIMORE HARBOR: SURFACE-WATER pH TRENDS, CURTIS BAY AT PENNINGTON AVENUE BRIDGE*

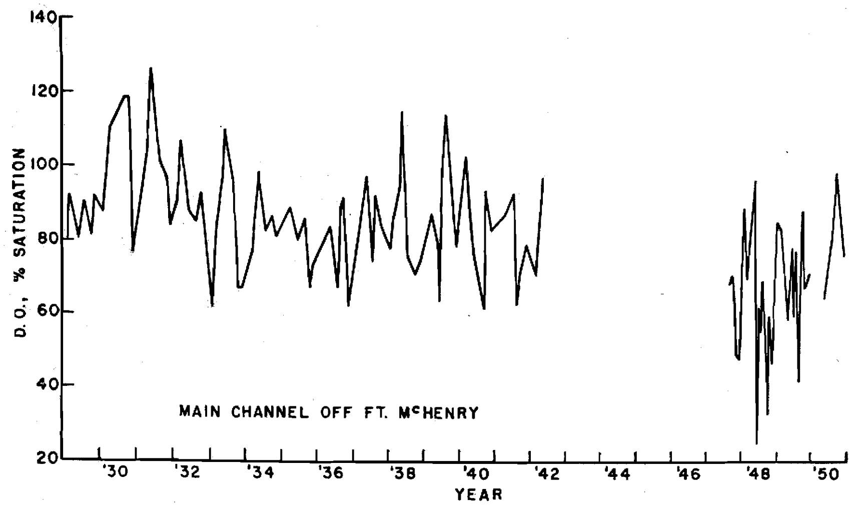
12-Month period (Aug. through July)	*Per cent probability of pH being equal to or less than stated value*			
	pH 7.0	pH 6.0	pH 5.0	pH 4.0
(1)	(2)	(3)	(4)	(5)
1940–41	95	54	4	0
1943–44	96	82	50	13
1945–46	97	88	58	19
1949–50	98	89	62	21

* From daily pH records of E. I. du Pont de Nemours & Co., Inc.

It is concluded that Harbor pollutional effects have been intensified during the last two decades. Peripheral waters have been affected more than those in the fairway. At the latter location, such deterioration as is evident is not extensive. However, the fact that Harbor water quality in general is trending downward should be recognized. Effects have become more widespread as the metropolitan area has expanded industrially and otherwise.

Future Conditions

Harbor pollution by domestic sewage will be modified by completion of proposed sewage diversions and provision of adequate treatment capacity at the City's Patapsco Sewage Works. If such improvements keep pace with the growth of population around the Harbor, pollution by domestic sewage will be a minor problem. Future conditions will then be determined for the most part by industrial waste discharges. Industrial production is increasing.



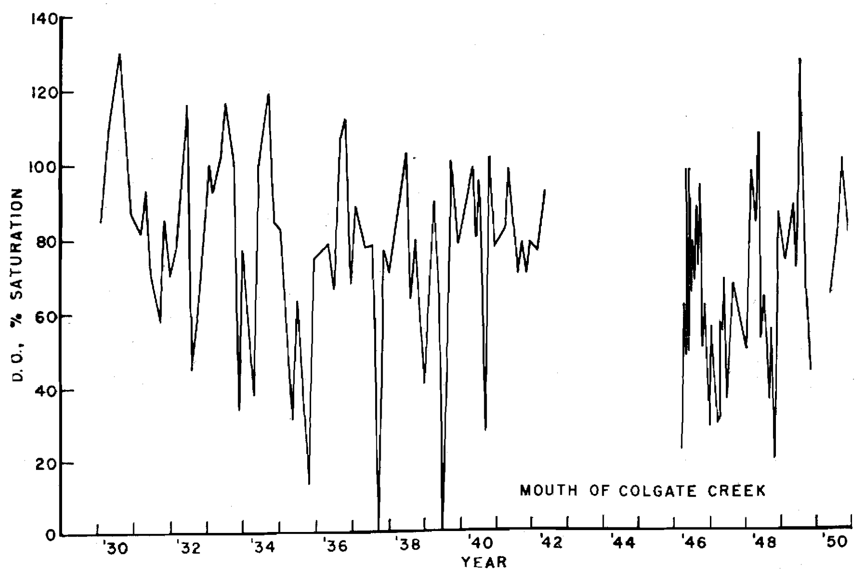
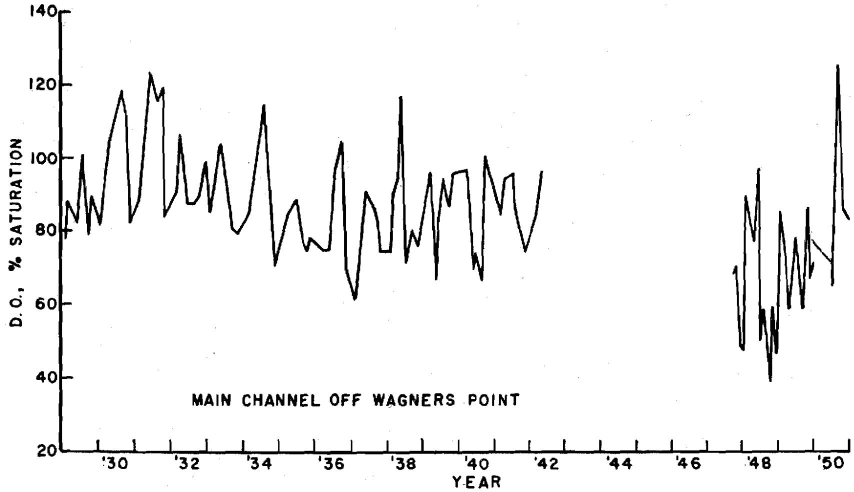


Fig. 31.

Baltimore Harbor
HISTORY OF SURFACE-WATER D.O.
AT FOUR UPPER HARBOR LOCATIONS
(Data 1929-42 and 1950, City Bureau of Sewers; other, Baltimore Harbor Project, Johns Hopkins University.)



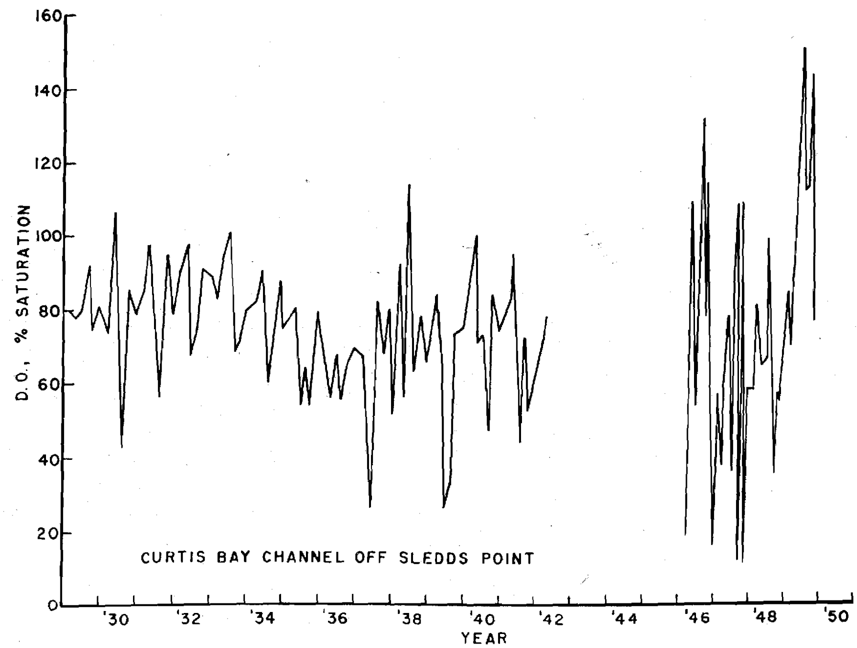


Fig. 31. (*Continued*)

Baltimore Harbor
HISTORY OF SURFACE-WATER D.O.
AT FOUR UPPER HARBOR LOCATIONS
(Data 1929-42 and 1950, City Bureau of Sewers; other, Baltimore Harbor Project, Johns Hopkins University.)

New plants are being encouraged to locate in the metropolitan area. In the absence of more public and private attention to industrial waste disposal than has existed, further degradation of Harbor water quality, particularly in peripheral areas, is to be expected.

Improvement in the general water quality of the Harbor, might be accomplished by either or a combination of both, of the following procedures.

(1) The system for dispersion of wastes can be improved. Since flushing rates for peripheral sections are now very low, a solution to the problem would appear to lie in diverting wastes to the main fairway, or in bringing the Harbor to the wastes. The first alternative involves construction of multiple-discharge, subaqueous outfalls of considerable length. Joint use of such facilities is possible, at least in the Curtis Bay area. The other alternative would entail pumping water from the main fairway or from adjacent less polluted creeks to the points where pollution is most severe. The net result of either method should be marked local improvement at the expense of slight degradation of the open water areas of the Estuary.

(2) The other possibility involves pollution abatement. It does not follow that waste treatment is necessarily required. Much can be accomplished within plants themselves to ameliorate the objectionable character of effluents. Processes may be converted and controlled, conservation measures instituted and the possibilities of by-product production sometimes realized. Only after full exploitation of each of these waste abatement procedures is public or private treatment warranted.

Each of these schemes requires expenditure of considerable private or public capital. It is fundamental that none of them is merited unless its cost is less than the value of resultant benefits. In this connection, it should be noted that the economy of pollution abatement is far from static. Constant development of improved processes and equipment in the fields of both industrial production and waste treatment point up the wisdom of frequent competent re-evaluation of the cost-benefit balance. No entirely satisfactory method for disposing of large quantities of waste ferrous sulfate-sulfuric acid solutions has been developed up to the present. However, current world shortages of sulfur and sulfuric acid have modified the economic values involved and stimulated research directed toward acid recovery.

It is technologically and economically feasible to reduce adequately oil discharges from industry. Such wastes are decidedly

SECTION VII.

CONCLUSIONS

The following general conclusions are derived from the investigation described in this report.

(1) In order of economic importance, the primary uses of water in Baltimore Harbor are for navigation, waste disposal, industrial water supply and recreation.

(2) The Harbor is polluted by discharge of sewage and industrial wastes to tributary streams and peripheral waters. The degree of pollution varies from negligible in the principal fairway to severe in innermost sections.

(3) Pollutional effects have been intensified during the last two decades. The trend is most pronounced near waste origins, but is discernible in the fairway of the Upper Harbor.

(4) Pollution of the Patapsco Estuary is predominantly industrial. In approximate order of their effect on water quality in the Harbor, important industrial effluents comprise those produced during manufacture of

a. titanium, lithopone and other pigments,

b. iron and steel and their by-products,

c. superphosphate fertilizers,

d. petroleum and its by-products,

e. miscellaneous organic chemicals,

f. brewer's yeast and

g. leather.

(5) Completion of scheduled improvements to public sewage collection and treatment facilities will soon reduce domestic sewage loads. Harbor water quality will then be affected primarily by process wastes from private industry.

(6) The Patapsco Estuary appears to have the ability to assimilate much greater loads of organic matter and acid than are being discharged at present. Degraded conditions are occasioned in limited peripheral areas by imposition of waste loads in excess of local assimilative capacities.

(7) Deposition of pollutional sediments within the Harbor

objectionable and need not reach the Harbor in appreciable quantity. Some of the past difficulties in this connection have resulted from oil discharges from transient shipping. This particular source of trouble can be controlled only by absolute enforcement of existing restrictive legislation, perhaps through a new approach on shipboard.

causes no significant increase in the volume of dredging required to maintain channels and anchorages within the Port.

(8) Flushing of the Harbor is effected primarily by local wind forces which are commonly able to overcome the weak current system generated by river and tidal forces. Water exchange in peripheral sections is negligible except during storms.

(9) Water circulation within the Estuary is so dominated by wind forces that any point in the Harbor may at one time or another be affected by wastes discharged at any other point in the Estuary.

(10) The public and private benefits which accrue from use of the Harbor for waste disposal are great.

(11) Existing conditions can be improved by transferring pollution loads from peripheral areas of limited assimilative capacities to the principal fairway, or by abating local waste discharges.

(12) There is no indication that waste disposal as normally practiced in the area has any significant effect on water quality in Chesapeake Bay outside Baltimore Harbor.

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APPENDIX A.

PRIOR WATER-QUALITY AND HYDROGRAPHIC INFORMATION FOR BALTIMORE HARBOR

A number of public and private agencies have concerned themselves with water conditions in the Port of Baltimore. For the convenience of future investigators, the sources and nature of noteworthy reference material encountered during the present investigation are presented here.

1. Baltimore Sewerage Commission

Annual reports published around the turn of the century by the Baltimore Sewerage Commission refer to Harbor conditions. Much of the information is qualitative and its usefulness is restricted. The Commission notes in its Annual Report for 1906: "As far as could be learned, there had never been a systematic study made of the pollution of the Patapsco River and its tributaries." The report describes what was apparently intended to be a routine sampling program for 15 locations in Back River and the Patapsco River—including Bear Creek.* Data are presented for samples collected during the period March 29 to April 24, 1906. Notation is made of the amount of sediment contained in the samples and values are included for residue on evaporation, D.O. and bacterial counts. No further reference to this work appears in subsequent Commission reports.

2. City Bureau of Sewers

The City Bureau of Sewers, with the cooperation of the Bureau of Harbors, has collected and analyzed Harbor water more or less continuously since 1929. The program was halted in 1942 but was resumed in 1950. Surface samples only are collected from 13 stations within the City. Unpublished records of analysis in the Bureau files include chlorides, pH, D.O., B.O.D., and M.P.N. of coliform bacteria.

In connection with site-location studies for a sewage treatment works to serve South Baltimore, the Bureau conducted float studies in the Inner Harbor. Six and 9-ft. floats were utilized in approxi-

* 1906 Annual Report, Baltimore Sewerage Commission, p. 55 and two tables fronting.

mately 40 series of observations made during April and May of 1922. Review of results on file in the Bureau shows that without exception the floats used were unduly sensitive to changes of wind direction and velocity.

3. City Bureau of Harbors

The City Bureau of Harbors cooperates with the Bureau of Sewers, as noted above, by providing a vessel for water sample collection. It also operates a recording tide gage from the municipal pier at the foot of President Street (Pier 7). Representatives from this office inspect establishments suspected of or found discharging objectionable wastes to the Harbor and requires abatement when such action is deemed advisable. The Bureau is at present responsible for most of the public dredging accomplished in the Inner Harbor. Records of these various activities are available in the files of this agency.

4. City Health Department

The Health Department of the City of Baltimore analyzes a limited number of Harbor samples for bacteria as part of its bathing beach program. The old Baltimore Sewerage Commission mentions Health Department work of this nature in its annual reports published nearly a half century ago. These data are unavailable, however, and would not be worth much if they were, due to differences between present and past bacteriological techniques. The Department presently analyzes samples from the immediate area of the bathing beach near the Harbor mouth at Fort Smallwood.

5. State Department of Health

Files of the Bureau of Sanitary Engineering of the State Department of Health contain a great deal of miscellaneous information concerning the Harbor. Most of it, however, records the results of investigation of particular pollution or nuisance complaints. Conditions in Curtis Bay were kept under surveillance for about 20 years prior to the last war, but no Harbor-wide studies have been made by the Bureau. It attempted in 1939 to coordinate activities of various public agencies interested in Harbor water conditions. Joint conferences were attended by representatives of the City Bureau of Harbors and Sewers, the Chesapeake Biological Laboratory (State Department of Research and Education) and engineers from the Bureau. Conclusions were reached regarding activities which were to be effected by each agency, including water sampling and study of the sources and nature of waste discharges. The program was never initiated, however, due to personnel shortages which developed at that time.

About 15 years ago, the Bureau was confronted with serious stream pollution problems which resulted from discharge of distillery waste. Accordingly, a number of stream sampling programs were initiated in 1936 and have been kept up on a more or less continuous basis. Information pertinent to the Harbor is available for Gwynns Falls and the Patapsco River. Samples are collected from four stations on the North Branch of the Patapsco at Westminster, five stations on the North Branch at Cedarhurst some 16 miles below Westminster, and on the main stem of the River at three stations extending downstream from Relay to the Old Annapolis Road bridge. Routine analyses conducted on these samples include suspended, volatile and total solids, B.O.D., D.O., pH, alkalinity, turbidity and color. These data, while limited, are reviewed critically in the stream pollution reports of the Bureau.

6. Chesapeake Biological Laboratory

Most of the published information about Harbor water conditions appears in reports of the Chesapeake Biological Laboratory. The Laboratory is concerned particularly with modifications of the biological economy of the Harbor and Chesapeake Bay which might result from waste discharges in the vicinity of Baltimore.

The laboratory began, in 1939, what was intended to be a continuing pollution and hydrographic study of the Harbor. The most important reports of this activity are summarized below.

(a) Olson, R. A., et al., Studies of the Effects of Industrial Pollution I. Curtis Bay Region, 1941, Pub. No. 43, Chesapeake Biol. Lab. (1941).

A report of study of Curtis Bay during the period January, 1938, through August, 1939. The investigators were concerned principally with effects of waste copperas discharged in the area. Results of float studies and water sample analyses are presented. Generally lowered summer pH values and oxygen tension were noted and it was concluded that tidal flushing in this section is practically nonexistent. Plankton studies indicated a removal of diatoms as a result of copperas flocculation following discharge. The recommendation was made that the practice of intermittent copperas discharge be modified to the extent of discharging the wastes as uniformly as possible. Aeration of the waste and sludge removal prior to discharge were suggested.

(b) Stern, Harry, Progress Report on Pollution Studies of the Patapsco R., unpublished MS., Chesapeake Biol. Lab., (April, 1942).

An analysis of physical-chemical data obtained during study of the Sparrows Point section during the period April through November, 1941. Local depression of pH and D.O. as a result of waste pickle liquor discharges was noted. The author concludes that more intensive hydrographic study was needed to appraise ultimate effects of these discharges.

(c) Davis, Charles C., Studies of the Effects of Industrial Pollution in the Lower Patapsco River Area, 2. The Effect of Copperas Pollution on the Plankton., Pub. No. 72, Chesapeake Biol. Lab., (June, 1948).

A report of study during the summer of 1941 of diatoms in the water and mud in the vicinity of Sparrows Point. Results confirmed the 1941 evidence obtained by the Laboratory to the effect that copperas flocculation removes diatoms from Harbor plankton and carries them to the bottom. On the other hand, decreased plankton concentrations in copperas-polluted areas could not be demonstrated.

(d) Stern, Harry, and Davis, Charles C., Pollution Studies in the Patapsco River, unpublished MS., Chesapeake Biol. Lab. (June, 1948).

The most ambitious prior Harbor study is described in this unpublished material. Emphasis was placed again on possible effects of waste copperas and pickle liquor discharges. Ten stations in Curtis Bay, Bear Creek and the Outer Harbor were sampled routinely during the period January-October, 1942. The conclusion was reached that pollutional effects were largely local. Data reported include pH, transparency (Secchi disk), chlorinity, temperature, D.O., and iron (total, soluble and ferrous).

(e) Sieling, Fred, Effects of Pollution at Baltimore on pH and Oxygen Content of Water, unpublished MS., Chesapeake Biol. Lab. (June, 1948). Also unpublished sampling results for 1946 and 1947.

A new series of sampling stations covering the entire Harbor was established by the Laboratory after World War II and this material contains results for the period February, 1946, through July, 1947. Recorded results include temperature, pH, D.O., salinity and total and ferrous iron.

7. State Water Pollution Control Commission

The Water Pollution Control Commission, established by the State legislature in 1947, is charged jointly with the Department of Health with controlling the pollution of the State's streams. With the exception of a few nuisance complaints, the Commission has made no special study of Baltimore Harbor pending completion of the current investigation. A stream sampling program was initiated during the summer of 1950 for stations on the main stem of the Patapsco River. Analytical data for samples collected from 11 stations from the confluence of the North and South Branches down to the Old Annapolis Road bridge a short distance above the Harbor are available.

8. United States Coast and Geodetic Survey

The Survey maintains a tide station at the Army Engineer Depot just above Ft. McHenry in Northwest Branch. In addition to records from a recording tide gage here, daily data from observations made here are available in the Washington office of the Survey for surface water temperature and density (salinity).

The best available information on the tides and currents of the region is presented in the Survey's Special Publication No. 162, *Tides and Currents in the Chesapeake Bay and Tributaries* (1930). In this bulletin, all of the meager current data for Baltimore Harbor and its approaches are reviewed and an analysis of the Ft. McHenry tide gage records for the period 1903-27 is presented.

9. United States Army Engineers

The Corps of Engineers, Department of the Army, is responsible under Federal law for improvement and maintenance of navigable waterways. Most of the public dredging in the Port of Baltimore is accomplished under the supervision and authority of the local district engineer. Complete records of this activity are filed in the Baltimore District office.

10. Miscellaneous

Several industries are sampling or have sampled water from the Port and the lower reaches of the River. In the Harbor itself, for example, the Pigments Department of E. I. du Pont de Nemours and Company, which operates a plant on Curtis Bay, makes daily pH determinations on samples collected from its pier and from bridges over Cabin Branch and Curtis Creek. The Gas and Electric Company of Baltimore maintains pH records for cooling water it takes from the Harbor in the vicinity of its various local power generating installations. Since World War II, the Test Department of this company has conducted a sampling program in the Curtis Bay section as an aid in controlling corrosion of its underwater lines. Analyses made on these samples include conductivity, pH, iron, D.O. and temperature.

The Gas and Electric Company also has pH, temperature and chloride data on the River a short distance above the Harbor. Prior to World War I, the Company took fresh water from the River through an intake near the Hammonds Ferry Road bridge (Wade's). Salt water occasionally penetrated this far upstream, so during the first war the intake was moved up to a point near the Pennsylvania R.R. bridge and below the present Calvert Distillery. Records are available for water conditions at this location. Use of river water was discontinued during World War II and has not been resumed. The Company operated seven sampling stations on the River above and below the Calvert plant during the 2-yr. period, 1942-44, and analytical data are in its files for pH, temperature, D.O., B.O.D., chlorides and iron.

APPENDIX B.

FIELD AND LABORATORY PROCEDURES AND EQUIPMENT

Field Sampling Methods and Apparatus

Water

In view of the shallow water depth involved, initial attempts were made to collect water samples by means of a simple hand-operated stirrup pump equipped with a length of suction hose which permitted sampling at depths up to 40 feet. The hose was lowered to the desired position and the pump operated for a few moments to flush out the line before collection of samples was begun. It was found, however, that samples obtained in this manner gave unsatisfactory D.O. results in that water was aerated in the pump barrel by air leakage around the piston stem. After the first few field trips in 1947, this technique was abandoned and subsequent water samples were collected with a 2-liter Kemmerer-Foerst sampler.

Water samples for bacteriological analysis were obtained in sterile glass bottles by means of a specially designed unit which permitted collection at any desired depth.

Bottom Mud

A free-falling coring tube (Woods Hole Oceanographic Institution) was used to collect mud samples. The device is essentially a weighted, lined brass tube which is driven into the mud by its own momentum. The upper end of the liner connects to a check valve in an adjustable frame to facilitate alignment of the lower end of the liner with the driving edge of the coring tube. The check valve assembly permits relief of upward vertical pressure components generated within the assembly during its descent and helps to retain the sample during the upward haul.

The corer was lowered over the side of the boat and permitted to fall freely to the bottom. Cores from 6 to 24 in. long were obtained, depending on the character of the bottom. After retrieving the apparatus, the plastic or glass liners used were removed from the coring tube, stoppered at both ends and stored in the laboratory at 4°C. until sample analysis was begun. Using a wooden dowel fitted with a rubber stopper, cores were extruded from the liners by pushing from the bottom end. Only a very slight pressure was required to move samples within the liner and it was possible to remove them in this manner with no marked distortion. Samples for analysis were then cut out from the cores at whatever level desired.

Industrial Waste

Gaging: Waste volumes were determined, when possible, by study of water consumption data furnished by plant management. In many instances, such information was incomplete or inaccurate and it was necessary actually to gage waste flows in one or more sewers at a given installation. The methods utilized in this work depended on field conditions. Many of the plants visited discharge wastes through submerged outlets or lines inaccessibly located beneath piers and docks. In addition, most of these sewers reached the Harbor after very short runs and it is necessary to consider back-water complications. At a few installations, some form of weir was available. Velocity measurements in conjunction with determination of the liquid depth in the sewer provided the only practicable method of getting at flows in many instances.

A number of techniques was utilized to obtain velocities. Where possible, adjacent manholes on straight sewer runs were located. Mean velocities were computed from the length between manholes and the time of passage between these points. Transit times were determined by the means most practicable for specific circumstances. Slugs of uranine dye or concentrated salt solution injected into the waste at an upper manhole were timed in their passage to a lower manhole. In the case of the dye, arrival at the lower observation point was determined visually. Conductance measurements described elsewhere afforded the means by which the time of arrival of the salt solution at the lower manhole was determined. Wood chips and other floating objects were also used to estimate velocities.

Sampling: Effort was made to collect representative industrial waste samples. In conference with plant management, the nature of the manufacturing processes involved were considered to determine probable variation in waste characteristics and flow. Decision was then reached as to the period and frequency of sample collection required to obtain representative composite samples. Samples were collected over variable periods of time up to 24 hrs. and brought into the laboratory for analysis.

Analytical Procedures

The chemical and bacteriological methods used in this study were essentially those of the ninth edition of *Standard Methods for the Examination of Water and Sewage* published jointly in 1946 by the American Public Health Association and the American Water Works Association. However, particular conditions occasionally required modification of the standard method. Such changes as were deemed advisable are noted below. It may be assumed that standard methods were followed if comment is lacking on detailed procedure.

Physical-Chemical

Temperature: On the basis of the use which was to be made of temperature data, it was decided that the simplest field technique would suffice. Measurements were made in the field when samples were collected. The first water withdrawn from the sampler was used to fill a standard B.O.D. bottle into which a mercury thermometer was inserted and allowed to remain while additional water was being withdrawn from the sampler for other determinations. After the brief period required to bring the thermometer and bottle to the sample temperature, the container was emptied, refilled with water from the sampler and the temperature determined and recorded to the nearest centigrade degree.

pH: A battery-powered Beckman electrometer equipped with glass and saturated calomel electrodes was used to determine pH to the nearest tenth of a unit. The instrument was standardized at the time of use in the field against a known buffer solution at the prevailing temperature. No additional temperature corrections were made.

Chlorides: The chlorinity of Baltimore Harbor water is several thousand parts per million. Accordingly, the Mohr technique presented in *Standard Methods* required modification. Silver nitrate titration in the presence of potassium chromate indicator was utilized, but the strength of the nitrate solution was such that an end-point could be reached upon delivery of from 2 – 10 ml. This solution was standardized against a sea-water substandard of known chlorinity prepared at the Woods Hole Oceanographic Institution. Results were reported as parts per thousand of chloride ion.

Strictly speaking, the term "chlorinity" as used in this report is the "chlorosity" of oceanography. Values reported in this study must be divided by the density of the water samples at 20°C to obtain the oceanographer's "chlorinity." For the Harbor salinity range, this correction is entirely insignificant for all practical purposes (about 0.2% difference) and was neglected.

Dissolved Oxygen: Water for D.O. analysis was drawn from the sampler into standard B.O.D. bottles. A short length of rubber tube which reached to the bottom of the bottle prevented undue aeration of these samples. The Rideal-Stewart modification of the Winkler method was used. In addition, 40% potassium fluoride solution was utilized immediately prior to addition of the permanganate reagent as prescribed in *Standard Methods*. Samples were fixed in the field at the time of collection and brought into the laboratory for final titration within a few hours.

Results were reported in ppm. of oxygen and as per cent saturation. The latter was determined from Hatfield's nomograph[1] which offers a convenient graphical means of determining saturation D.O. and per cent saturation from chlorinity, temperature and absolute D.O. values. The nomograph provides for relative humidity and barometric pressure variation corrections, but these refinements were considered unnecessary. A fixed effective atmospheric pressure of 754 mm., Hg, was utilized for saturation computations. This value was determined after study of local meteorological records and includes assumptions of a mean barometric pressure of 760 mm., a mean atmospheric temperature of 56°F. (13°C.) and a mean relative humidity of fifty-four per cent.

Biochemical Oxygen Demand: In general, *Standard Methods* was followed for determining 5-day, 20°C. B.O.D. With experience, it was possible to collect most of the B.O.D. samples directly in the field, using the field D.O. as the initial oxygen prior to standard incubation. Conditions were encountered occasionally which prevented direct sampling, such as high B.O.D., elevated water temperature (low D.O.) or low pH. Such samples were transported to the laboratory where they were brought to temperature, neutralized if the pH was below 5.0 and seeded with water from Sta. 5-T. Seed from this location was used because it is near the outfall from the City's Patapsco Sewage Treatment Works; water from this site undoubtedly contains most of the organisms typical of the Harbor environment. Necessary sample dilutions were prepared with *Standard Methods*' phosphate-buffered dilution water aged at 20°C.

[1] Hatfield, W. D., Nomograph for Dissolved Oxygen Saturation, S.W.J., *13*:557 (1941).

A walk-in, 20°C., air incubator was used and water seals were maintained on all samples.

The same B.O.D. technique was used on industrial waste samples, with the exception that it was usually more expedient to use Harbor water collected from the vicinity of the various plant outfalls for seed.

Total Iron: Iron was determined photocolorimetrically, using ortho-phenanthroline as the indicator and a Fisher filter electrophotometer. A 525-millimicron absorption filter was used and the detailed procedure was that of Caldwell and Adams.[2] At the time of collection, samples for iron analysis were drawn into small bottles containing 1 ml. of 3N HC1. This was done to dissolve iron floc commonly present in the Harbor water so that representative aliquots could be obtained for analysis. Results were reported as ppm. of Fe.

Electrolytic Conductance: Resistance values for Harbor water were determined *in situ* with a portable, battery-powered Industrial Instruments, Series R.C., conductivity bridge utilizing a dip-type cell on 50-ft. leads. The cell was determined in the laboratory to have a mean constant of 1.39 over the temperature range 15-30°C. A standard KCl solution of known equivalent conductance was used for this determination. Resistance observations were corrected to a standard reference temperature of 18°C., as described in Appendix C.

Ether-soluble Material: Ether-soluble mud fractions were determined on half of the sample from each core level. The material was air dried, ground to a fine powder, weighed and placed in a Soxhlet apparatus for extraction with petroleum ether for eight hours. The excess volume of extractant was reduced to approximately 10 ml. and evaporated to dryness in a weighing bottle. Results were reported as grams of ether-soluble material per kg. of dry solids.

Bacteriological

Coliform-organisms densities were estimated on the basis of confirmed results by the Most Probable Number technique, using Hoskins' tables.[3] For routine work, three tubes in each of three geometric dilutions were used. Presumptive results were obtained in lactose broth and confirmed in brilliant green bile G.B.).B).

[2] Caldwell, B. H., and Adams, R. B., Colorimetric Determination of Iron in Water with o-phenanthroline, J.A.W.W.A. *38*:727 (1946).
[3] Hoskins, J. K., Most Probable Numbers for the Evaluation of Coli-Aerogenes Tests by Fermentation Tube Method, Reprint No. 1621, Public Health Reports (Revised 1940).

Standard Methods B.O.D. dilution water was used in making up dilutions and Difco dehydrated media were used exclusively.

Bottom mud samples for bacteriological analysis were obtained with the coring tube described previously. Sterile glass liners were used and plugged for transportation with autoclaved stoppers. Mud was taken into the laboratory as soon as possible after collection, sampled aseptically at any desired level and the portion selected for analysis suspended in 100 ml. of sterile dilution water. This mud suspension was inoculated in each of three tubes in three geometric dilutions. Lauryl tryptose broth was used for these mud presumptives because of its specificity for coliform organisms. Confirmation was effected in B.G.B. The mud suspension after sampling was collected on asbestos in a Gooch crucible and its dry weight determined after drying at 103°C. Results were reported as M.P.N. per gram of dry solids.

Instead of using gas tubes in this investigation, a "hot-wire" technique was utilized. Gas production, usually evident by surface frothing, was detected by flaming an inoculation needle red hot and plunging it into the broth. A gas-saturated broth will effervesce strongly along the hot wire. This is particularly true for media containing surface-tension depressants. When positive presumptive tubes were encountered, the hot-wire testing stroke was used for the transfer to the confirming medium.

A number of parallel bacteriological analyses was conducted early in the investigation by means of which the hot-wire and fermentation-tube techniques were compared. Lactose tubes containing fermentation vials were inoculated in three geometric dilutions, 18 tubes per dilution. At the standard time intervals, the fermentation vials were read and the same tubes tested with the hot wire. All positive tubes by either method were confirmed in B.G.B., again on the basis of both techniques. Very similar results were obtained and, considering the reliability of a 3-tube, 3-dilution M.P.N. value and the time saved by use of the hot-wire technique, it was decided to adopt this method as standard procedure for the investigation. It is noteworthy that during the comparison study, fewer weak reactions were encountered in the hot-wire tests.

Hydrographic Measurements

Extensive use was made of standard U. S. Coast and Geodetic Survey hydrographic charts for Baltimore Harbor. The mean tidal range at Baltimore is only about 1 ft. so that depth measurement was not complicated seriously. Chart depths were checked on a number of occasions by means of a Bludworth sonic sounder. No instance was encountered where these depths did not check very closely.

Subsurface current measurements were effected with two types of current meters. Through the courtesy of Mr. William S. von Arx of the Woods Hole Oceanographic Institution, a propellor meter similar to the standard Price apparatus was obtained. This instrument is designed so that propellor revolutions produce an Emf. pulse in a closed electrical circuit. The number of pulses per unit of time is detected acoustically with headphones and converted to current magnitude by means of a rating curve.

The particular von Arx meter used had the disadvantage of not indicating current direction, so an Ekman meter was used to provide supplementary current information.

Surface currents were observed with a 1-in. diameter current pole weighted at one end so that it floated in an upright position with a 4-ft. submergence. To minimize wind error, the weight was adjusted to provide not more than a 3 or 4-in. projection of the device above the water surface.

APPENDIX C.

CONDUCTANCE MEASUREMENTS IN BALTIMORE HARBOR

The salinity and composition of full sea water at a given location are practically constant. Chloride or conductance measurements, then, are convenient study aids for determining the dilution and dispersion of fresh water discharged into salt water of known salinity.

It is desirable to obtain the salinity information as rapidly as possible in the field so that important or unusual conditions may be studied as encountered. Electrical conductance of water may be determined rapidly *in situ,* and is related to the concentration of contained salts. Together with temperature measurements, it affords a rapid means of following salinity changes. Comment which follows develops the relationship between electrical conductance measurements and chloride-ion concentration for Baltimore Harbor.

The following terms are defined:

Specific resistance, r: the resistance in ohms of a unit cm. cube; i.e., the resistance between opposite faces of a 1-cm. cube of the material under consideration.

Specific conductance, λ: the inverse of specific resistance—expressed in reciprocal ohms or "mhos."

Equivalent conductance, Λ: a measure of the conducting power of all the ions produced by one equivalent of electrolyte in a given solution. Defined as the product of the specific conductance and the volume containing one equivalent of the solute.

Electrolytic solutions, like metallic conductors, obey Ohm's law which relates the electrical pressure or emf. applied to a conductor and the strength of the current passing. The law states that the current strength, I, is directly proportional to the applied emf., E, and inversely proportional to the resistance, R. The resistance of any uniform conductor varies directly as its length, L, and inversely as its cross sectional area, A. Therefore, according to Ohm's law,

$$R = rL/A \text{ ohms}$$

and solving for the specific resistance,

$$r = RA/L \text{ ohms}$$

By definition, specific conductance is the reciprocal of r, so

$$\lambda = L/AR \text{ mhos}$$

Substituting the value of λ in the expression for Λ and solving for the observed resistance, R,

$$R = \frac{V}{\Lambda} \times \frac{L}{A}$$

From the foregoing, it may be shown that the ppm. of electrolyte are given by the expression:

$$\text{ppm.} = \frac{\text{equiv. wt. of electrolyte} \times L/A \times 10^6}{R \times \Lambda}$$

In practice it is inconvenient to work with electrode spacing and area, so the quantity L/A is determined empirically for a given electrode assembly (cell) from solutions of known equivalent conductance. The resultant value is termed the "cell constant."

As the concentration of solution decreases, its specific and observed resistances increase regularly. In addition, resistance varies with temperature. For most salts in aqueous solution, resistance decreases slightly more than two per cent for each degree rise in temperature in the neighborhood of 18°C. (negative temperature coefficient). The temperature effect on resistance may be formulated as follows:

$$R_{18} = R_t \,[1 + 0.025\,(t\text{-}18)\,]$$

where R_{18} is the observed resistance at the standard reference temperature of 18°C., R_t the resistance at the test temperature and t the temperature of testing in C°.

It was appreciated early in the investigation that the Harbor water contains large quantities of ionizable chemical wastes which would influence conductance measurements and perhaps obviate use of such values in determining the chlorinity. Accordingly, a number of concurrent conductance and chloride measurements were made during routine sampling operations. Fig. C-1 shows the correlation between these determinations after correction of observed resistances to the 18°C. reference temperature.

Since the buffer capacity of brackish water is high, it is reasoned that Harbor water samples with pH values outside the range 5 to 9 must contain relatively high concentrations of industrial wastes. No pH as high as nine was encountered during the study, but values less than five were found frequently in tributary areas. Analytic data for these acid samples were not included in fixing the curve.

As a plotting aid, the indicated points are means of some 124 observations. A single point in the chloride range 4 – 8 ppt. may rep-

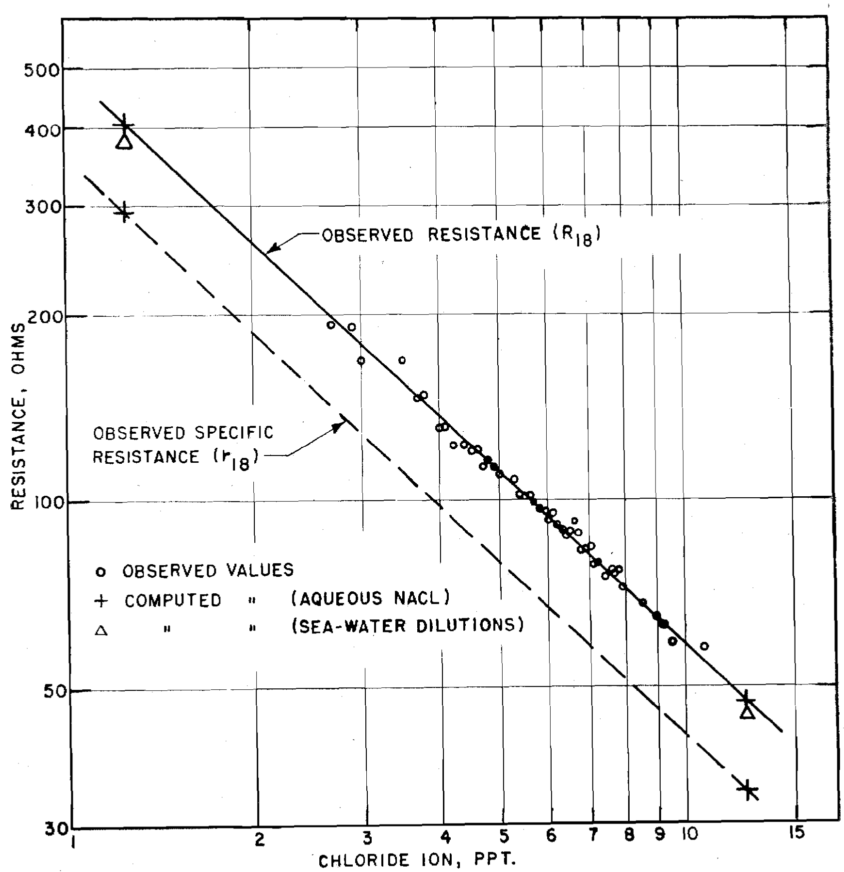

Fig. C-1.
CONDUCTIVITY OF BALTIMORE HARBOR WATER

present as many as 12 paired values. In every case, points with the greatest deviation from the line of best fit are single values which lack the stability of the other points.

Similar values for pure NaCl[1] and sea-water dilutions[2] were computed. Their maximum deviation from Harbor curves was slightly less than six per cent. It was concluded that this degree of error was far offset by advantages inherent in field use of the conductance technique for determining salinity during special hydrographic studies, provided such procedure was restricted to locations where extreme pH values are not encountered. For routine sampling, it was more expedient to determine chlorides by the usual laboratory procedure.

[1] Equivalent conductance values from *International Critical Tables* 6:230 (1929).
[2] Equivalent conductance values from Thomas, B.D., *et al.*, The Electrical Conductivity of Sea Water, Jour. du Conseil, 9:28 (1934).

APPENDIX D.

THE OXYGEN ECONOMY OF BALTIMORE HARBOR

The oxygen content of surface waters reflects a dynamic equilibrium between reoxygenation and deoxygenation processes, many of which are time and temperature functions. Oxygen is supplied by

a. D.O. in wastes

b. added dilution

c. reaeration, or solution of atmospheric oxygen

d. photosynthesis, or the metabolic activity of certain aquatic plants.

Deoxygenation occurs as a result of

a. B.O.D. of organic wastes

b. benthal or bottom-mud requirements

c. natural B.O.D. in the receiving stream

d. chemical demands.

These components are appraised respectively for Patapsco Estuary conditions.

Oxygen Resources

The concentration of D.O. in natural surface waters is governed fundamentally by Henry's law which states that at a given temperature the solubility of a gas in a liquid is proportional to the pressure of the gas over the solution. Since the partial pressure of oxygen in the atmosphere is fairly constant, there is an upper limit to the amount of oxygen which can be dissolved from the air under natural conditions. This amount is termed the saturation value and the oxygen content of the water in contact with the atmosphere will tend to reach this equilibrium value. Both salinity and temperature rises reduce the saturation value. D.O. saturation for Baltimore Harbor water at ordinary winter temperatures is about 13 ppm. In summer, this is decreased to approximately 8 ppm.

From Pollutants

The dissolved oxygen content of wastes discharged to the Estuary is negligible relative to other sources and may be neglected.

From New Water

The volume of new water entering the region is indefinite and highly variable. Using the estimates already cited, a mean land-water runoff to the Harbor of 500 cfs. containing 8 ppm. of D.O., approximately 22,000 lbs. of oxygen are brought into the Estuary daily from this source. It appears that much larger volumes of water enter from the Bay, so correspondingly greater oxygen resources are available from this source, provided that inflow occurs at the surface. When Bay water enters along the bottom in summer, little, if any, oxygen is made available. The oxygen content of such water is virtually nil, a condition which is believed to reflect water circulation patterns within the Bay.

The industrial waste survey of this investigation shows that at least 475 tons of acidity (as equivalent $CaCO_3$) are neutralized each day by the natural alkalinity of the Harbor water. Since alkalinities well up into the Port are normal, it is reasoned that the volume of "new" water reaching the Estuary must be at least sufficient to afford equivalent natural alkalinity equal to the weight of acidity discharged. This volume, Q, may be computed as follows: assume a value of 50 ppm. as $CaCO_3$ for the alkalinity of Bay water off the Harbor. Then,

$$Q \times 8.34 \times 50 = 475 \times 2{,}000$$

$$\text{and } Q = 2{,}280 \text{ mgd. or } 3{,}530 \text{ cfs.}$$

If this water were saturated with oxygen in summer, it could bring into the Estuary 2,280 x 8 x 8.34 = 152,000 lb. of oxygen per day.

From Reaeration

Oxygen enters a stream through the water surface and is moved downward by diffusion and physical transfer, that is, by mixing and stirring. Rates of solution are directly proportional to the saturation deficit of the water and also depend upon depth, turbulence and temperature.

Since diffusion is the fundamental process by which dissolved oxygen moves from a region of relatively high to one of lower concentration, tending always to equalize itself throughout the water volume, Phelps has formulated the oxygen uptake of an undersaturated body of quiescent fresh water exposed to the atmosphere.[1] The original expression is cumbersome and for practical application he has simplified it to the following:[2]

[1] Black, W. M. and E. B. Phelps, Report to the N. Y. Board of Estimate and Apportionment Concerning the Location of Sewer Outlets and the Discharge of Sewage into N. Y. Harbor, March 23, 1911 (reprinted as Vol. VII of Contributions from the Sanitary Research Laboratory and Sewage Experiment Station, Mass. Inst. of Tech., (1911).

[2] Phelps, Earle B., *Stream Sanitation*, Wiley, New York (1944), p. 150, *et seq.*

$$\log r_o = 1.85 + 0.5 \log K$$

where r_o is the reaeration rate at 100 per cent oxygen deficit, and

$$K = \frac{\pi^2 at}{4L^2}$$

In the argument (K), π = a constant, 3.14

a = a proportionality constant, the coefficient of diffusion.

t = time, and

L = the stream depth.

For depth in feet and time in hours, Phelps experimentally determined a mean value for the diffusion coefficient (a) of 0.00153 for fresh water at 20°C.

Quiescent stream conditions in nature are rare and some account must be taken of the influence of turbulence or mixing on the simple diffusion concept. Mixing may be regarded as a process which produces a decrease in the effective depth of the body of water under consideration. Such an assumption is based on the fact that mixing breaks up the saturated surface film into smaller masses which are then brought into contact with less saturated water, thus accelerating the relatively slow diffusion process. Reaeration under natural stream conditions is visualized as occurring in a series of short periods of quiescence followed by instantaneous mixing; reference is made to the "period between mixes" or "turnover time" of a given stream stretch. Application of the Phelps diffusion formula to field studies has indicated effective turnover times of from 5 - 30 minutes for fresh water streams. Total aeration per hour is thus considered to be the product of the amount per period and the number of period per hour.

Fig. D-1 has been prepared from the above formula. It illustrates the effects of turbulence and depth upon reaeration rates. Practical application of Phelps' formula is hampered by lack of means for determining actual turnover periods. In the absence of such information for the Patapsco Estuary, the magnitude of reaeration at Baltimore must be estimated from rates observed elsewhere.

Streeter reports surface values for "ordinary flowing rivers" ranging from 5 - 20 grams per square meter per day (45 to 178 lb. per acre) at 100% deficit.[3] He notes that they "may be as low as

[3] Streeter, H. W., *Modern Sewage Disposal*, Federation of Sewage Works Assns., New York (1938).

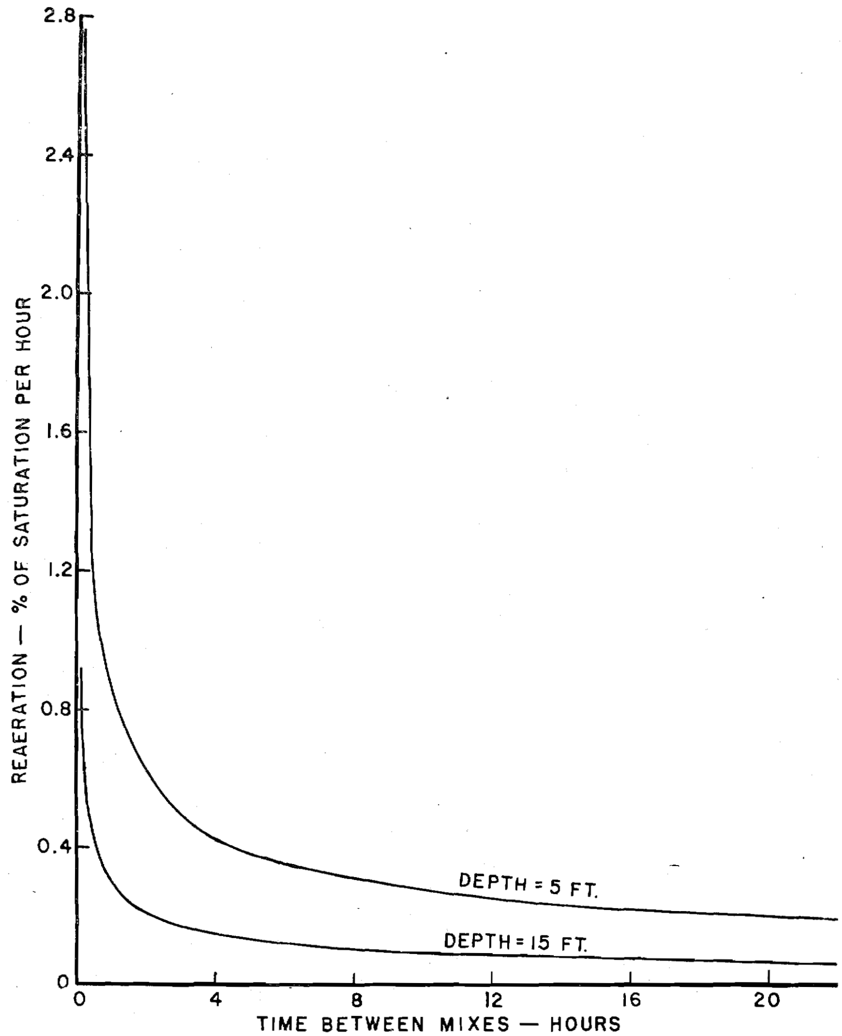

Fig. D-1.

INFLUENCE OF DEPTH AND TURNOVER TIME UPON REAERATION AT 20° C.
(after Phelps)

two grams or less in very quiescent waters and as high as 50 or 60 grams in shallow, highly turbulent riffles." For summer conditions in Baltimore Harbor, where velocities are generally less than one fps. and turbulence is low, the lower rate of about five grams, or 45 lb.per acre per day, appears reasonable. This value compares well with rates suggested by Imhoff and Fair for sluggish streams and large impoundments.[4] Assuming an effective water depth of 15 ft.,this rate is equivalent to 1.1 ppm. per day, or about 0.6% of saturation per hour in warm weather.* From Fig. D-1, a turnover period approaching one hour is indicated—a not unlikely value.

It is to be noted that rates are reduced proportionately for deficits other than 100%, and that oxygen added in terms of concentration units increases for shallower depths. Moreover, temperature rises increase reaeration rates. In terms of quantity units, the rate of increase is about 1.5% per C° rise in water temperature. Summer deficits over the Estuary average close to 25% (75% D.O. saturation) for the upper 15 ft. of water, so that reaeration must be about 1 x 25/100 = 0.25 ppm. per day. Although seemingly small, the water volume involved is so large (12 x 10^9 cu. ft.) that the actual weight of oxygen dissolved from the atmosphere approaches

$$\frac{0.25 \times 8.34 \times (12 \times 10^9) \times 7.48}{10^6} = 187{,}000 \text{ pounds per day.}$$

Summer reaeration at 50% and 25% saturation would be 374,000 and 561,000 pounds per day, respectively, assuming maintenance of the deficits.

* $\text{ppm. per day} = \dfrac{\text{lb. per acre per day}}{2.71 \times \text{ft. of depth}}$

$\text{per cent saturation per hour} = \dfrac{\text{ppm. per day} \times 100}{24 \times \text{saturation ppm.}}$

From Photosynthesis

Light in the presence of the green plant pigment, chlorophyll, enables the synthesis of complex organic compounds from simple inorganic ones. Oxygen produced during this process is termed "photosynthetic" oxygen and may represent a substantial although somewhat unreliable contribution to the oxygen economy of surface waters.

A marked photosynthetic effect was noted during hydrographic operations early in the present investigation. Accordingly, the matter received special consideration during the summer and fall of 1949. Oxygen produced by photosynthesis was determined quantitatively for three Harbor locations: 1) off Sevenfoot Knoll at

[4] Imhoff, Karl, and G. M. Fair, *Sewage Treatment*, Wiley, New York (1940), p. 304.

the entrance to the Port, 2) off Hawkins Point near Fort Carroll, and 3) in Northwest Branch just above Fort McHenry.[5] Effective insolation at these locations varied as a result of cloud cover, industrial smoke and haze, natural and pollutional turbidity and other factors. No consistent advantage was apparent at any particular station, so data were appraised *in toto*.

During the period of study, the lower limit of photosynthesis ranged from 10.3 to 12.8 ft. below the water surface and averaged about 11 ft. The range of the depth at which photosynthetic and B.O.D. rates were equal (compensation depth) was less, being from 1.7 to 8 ft., with an average slightly more than 5 ft. The observed variation of mean oxygen production rates with depth is shown in Fig. D-2. From these data, the magnitude of the photosynthetic effect during the period of study is estimated to have approached 1 ppm. daily in the upper 11 ft. of Harbor water. The water volume involved amounts to 9.7×10^9 cu. ft.; so, in terms of quantity units, oxygen was produced photosynthetically at a rate of some 600,000 lb. per day.

The availability of oxygen is a matter for speculation. Surface-water supersaturation was encountered frequently in the Estuary during the daytime. Under such conditions, dissolved oxygen tends to be lost to the atmosphere. The estimated value of 600,000 lb. per day probably represents an upper limit for oxygen derived from photosynthesis during clear summer weather.

Oxygen Demands

Items which must be entered on the debit side of oxygen balance include the B.O.D. of putrescible pollutants and the requirements of chemical wastes which combine directly with oxygen after dilution in a watercourse. Stream B.O.D. may be divided into the flowing load, that which is exerted by substances dissolved or suspended in the water, and the benthal or bottom-mud fraction.

The Flowing Load

It is well established that for many organic substances the rate of progressive exertion of B.O.D. in the absence of sedimentation effects is proportional to the concentration of remaining organic matter.[6] Stated mathematically,

$$\frac{dy}{dt} = 2.3k\ (L\text{-}y)$$

[5] Hull, C. H., Photosynthetic Oxygen Producton in Baltimore Harbor, unpublished master's thesis, The Johns Hopkins University, (1950).
[6] Theriault, E. J., The Oxygen Demand of Polluted Water, Public Health Bulletin No. 173 (1927)

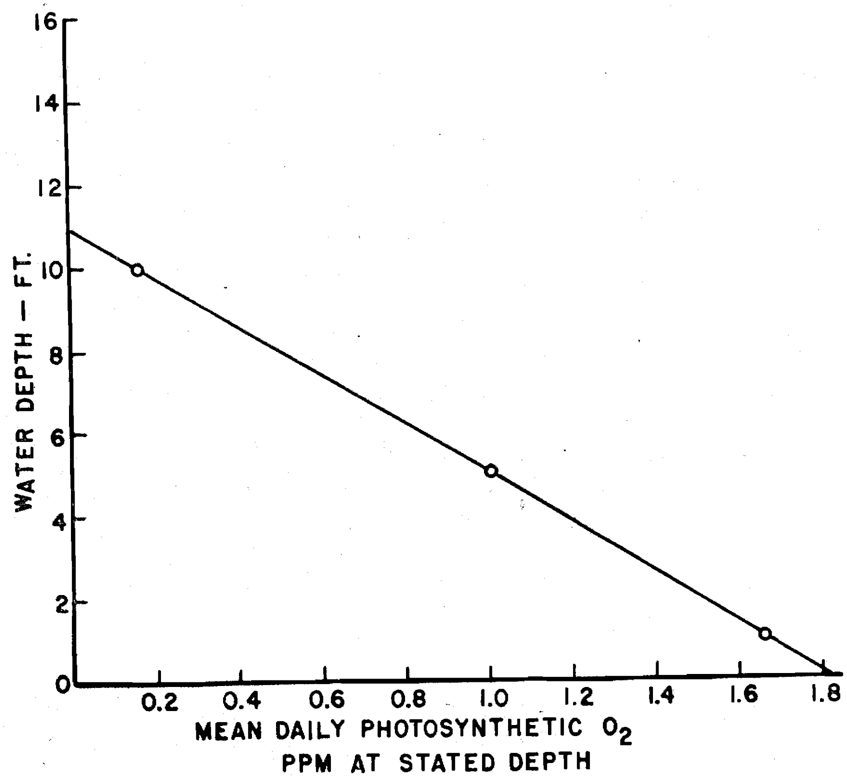

Fig. D-2.

Baltimore Harbor
OBSERVED RATE OF PHOTOSYNTHETIC OXYGEN PRODUCTION
Aug.-Sept., 1949
(after Hull)

where y = oxygen requirements at time (t),
L = ultimate oxygen requirements of the material, and
k = a proportionality constant defining the velocity of the reaction.

In the integrated form, the above equation becomes

$$y = L\,(1 - 10^{-kt})$$

where y = the aggregate oxygen requirement for the period of time (t).

It is believed that stabilization proceeds in two somewhat overlapping stages. The first is thought to represent largely oxidation of carbonaceous materials and the second, conversion of nitrogenous compounds through the nitrogen cycle to nitrates.

Temperature rises increase B.O.D. rates. This effect has been formulated by Streeter and Phelps as follows:[7]

$$\frac{k'}{k} = 1.047^{(T'-T)}$$

where k′ and k are the B.O.D. rate constants at Centigrade temperatures T′ and T, respectively.

This means that the reaction velocity is accelerated by 4.7% for each successive rise of one C.°, or by 58% for a 10 C.° rise.

The progressive exertion of Harbor-water B.O.D. was studied in the laboratory and found to conform to fresh-water experience. A typical analysis is presented in Fig. D-3 and shows clearly the two stages to which reference has been made. Curves describing the

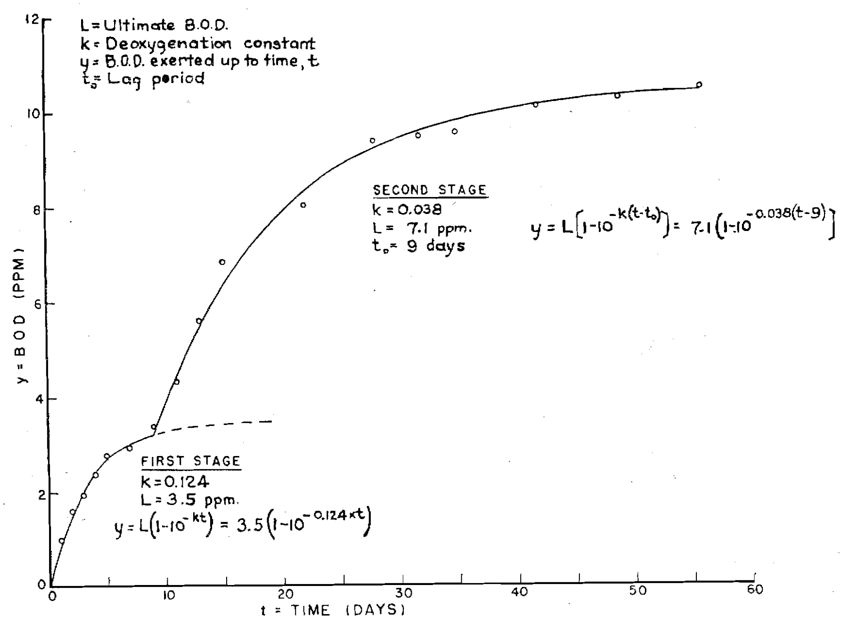

Fig. D-3.

LONG-TIME B.O.D. OF BALTIMORE HARBOR WATER

course of stabilization have been fitted graphically to the observed values. The second-stage equation is valid only for positive values of the quantity $(t - t_o)$. It is of note here that the ratio of ultimate second-stage demand to the first-stage requirement is 2.3 and that a

[7] Streeter, H. W. and E. B. Phelps, U. S. Public Health Bulletin No. 146 (1925), pp. 7-9.

similar ratio for rates is 0.31. These relationships are within ranges reported for polluted fresh water.[8]

The effect of the temperature range at Baltimore on the rate of B.O.D. satisfaction is illustrated in Table D-1. These data were calculated from the B.O.D. equation, using a k_{20} of 0.124 from Fig. D-3 and the Phelps-Streeter expression for the temperature effect. At maximum summer temperatures, B.O.D. is exerted at a rate which is about three times that which obtains for minimum winter temperatures. This explains, in part, why the warm-weather period is critical as concerns oxygen conditions in the Harbor.

TABLE D-1

BALTIMORE HARBOR: EFFECT OF TEMPERATURE ON BIOCHEMICAL OXYGEN DEMAND RATE

Temperature °C.	*1st-stage k*	*Time for 90 per cent completion of 1st-stage B.O.D. days*
5	0.062	16.2
10	0.078	12.8
15	0.098	10.2
20	0.124	8.1
25	0.156	6.4
30	0.196	5.1

While it is customary to evaluate relative pollutional strengths in terms of 5-day B.O.D. at 20°C., it is true that ultimate stabilization requirements are satisfied in the stream. Under reasonably constant conditions of loading, stream flow and temperature, the oxygen demand exerted in a particular stream stretch by nonsettleable pollutants is the demand of the daily waste discharge at stream temperature and over a time interval equal to the time of passage through the reach.

Flushing times for the Estuary approach several weeks. It appears that the ultimate oxygen requirements of most of the organic wastes discharged to the Port are exerted within the Harbor proper. Under such conditions, the upper limit of demand is the ultimate requirements of the nonsettleable pollutional load for one day. In

[8] Thomas, Harold A., Jr., Analysis of the Biochemical Oxygen Demand Curve, Sewage Works Journal, *12*: 504 (1940).

this connection, it is important to note the effect of temperature upon summer conditions in the Patapsco Estuary. Since the rate of stabilization is accelerated at increased temperatures, ultimate oxygen requirements are exerted within a shortened distance of stream flow. Most of the organic loading at Baltimore reaches the Estuary via the Inner Harbor. This section of the Port is therefore required to meet a disproportionate share of summer oxygen demands under the present load distribution.

The ultimate B.O.D. of materials reaching the Harbor in a single day are evaluated in Table D-2. The total shown in this table is the weight of oxygen which must be provided to stabilize aerobically the pollutional load added daily to the Estuary. The total of about 100,000 lb. at 20°C. cannot be taken as other than an approximation because of the nature of assumptions required in its calculation and the incompleteness of basic data.

TABLE D-2

BALTIMORE HARBOR: ESTIMATED ULTIMATE BIOCHEMICAL OXYGEN DEMAND IMPOSED BY KNOWN POLLUTIONAL DISCHARGES

(as of December, 1950)

	Origin	*Ultimate 20°C. B.O.D. lb. per day*
1.	Antecedent natural and artificial B.O.D. reaching Patpasco Estuary via tributary streams	19,800
	a. Patapsco River @ 13,000 lb./day[1]	
	b. Jones Falls @ 5,800 lb./day[2]	
	c. Gwynns Falls @ 11,000 lb./day[3]	
	19,800 lb./day	
2.	Raw and treated domestic sewage	51,000
	a. First stage @ 17,000 lb./day[4]	
	b. Second stage @ 34,000 lb./day[5]	
	51,000 lb./day	
3.	Manufacturing wastes and industrial sanitary sewage[6]	35,000
	TOTAL	105,800

[1] From laboratory study of long-time B.O.D. and stream discharge estimates. Only one stage observed.
300 cfs. x 8 ppm. x 5.4 = 13,000 lb./day

[2] From laboratory study of long-time B.O.D. and stream discharge estimates.
54 cfs. x 20 ppm. x 5.4 = 5,800 lb./day

[3] From laboratory study of long-time B.O.D. and stream discharge estimates.
58 cfs. x 35 ppm. x 5.4 = 11,000 lb./day

[4] 0.17 lb./day from equivalent population of 100,000 as estimated in Section III of this report; includes allowance of one-third for removal of solids to Harbor bottom.

[5] Twice the first-stage demand.

[6] Estimated from data of Section III of this report.

There is, in addition to the added load, the B.O.D. imposed by the death and decay of aquatic biota. A reasonable 5-day 20°C. value for this in Baltimore Harbor is one ppm. From the fundamental B.O.D. equation, using a velocity constant, k_{20}, of 0.12 and converting to 25°C., and 5°C. for summer and winter conditions, respectively, this demand categeory amounts to 420,000 lb. per day in warm weather and 180,000 lb. per day during winter.

The Benthal Load

Although the qualitative influence of bottom deposits upon the D.O. of supernatant water is well recognized, little useful information is available for natural conditions. Fair and his associates have studied benthal decomposition in the laboratory under controlled conditions.[9] As measured by the utilization of oxygen in overlying water, they observed times for 90% stabilization of river muds of 1.5 years, compared with a similar time of about 8 days (1st stage) for aerobic stabilization of polluted water. Rates range widely between those of purely aerobic and anaerobic digestion. Much of the ultimate aerobic demand of such deposits may never be exerted. Fair concludes that the oxygen requirements of this type of stabilization are limited by the rate at which soluble products of anaerobic digestion are diffused upward into supernatant water, rather than by the actual rate of digestion.

The magnitude of mean benthal requirements may be appraised by considerating the amount and character of sediments deposited within the Harbor. From knowledge of aerobic and anaerobic digestion, some concept of this demand category may be gained. Studies indicate that as much as 1 lb. of oxygen may be required for aerobic stabilization of a pound of volatile sewage solids. As little as 10% of this weight of oxygen is utilized for anaerobic digestion of similar material.

It is estimated from this study that the rate of sediment accumulation within the Harbor is approximately 750,000 cu. yd. per year. Examination of mud samples from the Harbor discloses that the wet material has a mean specific weight of 71 lb. per cu. ft. and is 22% solids. On a dry-weight basis, about 13% of the solids are volatile (decomposable). From these data, the estimated mean daily rate of deposit of organic debris is:

[9] Fair, G. M., *et al.*, The Natural Purification of River Muds and Pollutional Sediments, Sewage Works Journal, *13*:270 (1941).

$$\frac{750{,}000 \times 27 \times 71 \times 0.22 \times 0.13}{365} = 112{,}000 \text{ lb. per day}$$

Average daily benthal demands thus range somewhere between 10,000 and 100,000 lbs., probably falling closer to the larger figure. However, this computation makes no allowance for the influence of ferric hydroxide decomposition upon the standard determination for volatile solids.

The effect of the seasonal temperature cycle at Baltimore upon benthal requirements is important as regards observed conditions. Under uniform loading and temperature conditions, an equilibrium storage of deposited material is reached at which the benthal demand equals the ultimate requirement of one day's deposition. The stabilization rate rises and falls in nature with the seasonal temperature cycle and there occurs a corresponding fluctuation of "stored" mud. The amount of accumulated deposit increases as rates drop in the cold season. In the spring and early summer, rising mud temperatures accelerate stabilization of the augmented storage. The daily demand under these conditions may be several times that of one day's deposition. Moreover, the active decomposition which characterizes this season may impose sudden overwhelming oxygen demands as mud and anaerobic decomposition products are lifted into overlying water by gaseous ebullition.

Chemical Requirements

The only waste encountered during this investigation which possessed appreciable chemical or immediate oxygen demand and which was discharged in sufficient quantity to merit consideration in this connection was ferrous sulfate from pigment plants and the steel mill. Assuming that this hydrolyzes to $Fe(OH)_2$ and this in turn is oxidized to $Fe(OH)_3$, 53 lb. of oxygen will combine stoichiometrically with the iron in each ton of waste sulfate as $FeSO_4$. For the estimated ferrous sulfate loading of 400 tons per day, 21,200 lb. of oxygen are utilized.

APPENDIX E.

HYDROGRAPHIC COMPUTATIONS FOR BALTIMORE HARBOR

DERIVATION OF EXPRESSIONS FOR TIDAL CURRENT VELOCITIES ON TRANSVERSE SECTIONS

The water volume, Q, which passes through any complete transverse section of area A between low tide and high tide is given by Sz, where S is the water surface area above the section and z is the mean tidal range. But Q also equals AvT/2, where v is the mean current velocity during the half-tidal period, T/2, in which flow occurs. Therefore,

$$Sz = AvT/2$$

$$\text{and } v = \frac{S}{A} \times \frac{2z}{T}$$

Flow is nonuniform across the section. The mid-channel velocity, v_c, is about one-third larger than the mean velocity on the section. So:

$$v_c = \frac{S}{A} \times \frac{8z}{3T}$$

The mean tidal range at Baltimore is 1.1 ft. and the tidal period is about 12.42 hr., or 44,700 seconds. Therefore, for areas in sq. ft.:

$$v = \frac{S}{A} \times 4.9 \times 10^{-5} \text{ fps.}$$

$$\text{and } v_c = \frac{S}{A} \times 7.7 \times 10^{-5} \text{ fps.}$$

Maximum currents may be calculated from the fact that the ratio of maximum to mean velocities is approximately $\pi/2$.

Application of Ketchum (Woods Hole) Hypothesis To Determination of Flushing Time of Patapsco Estuary

Ketchum has proposed an empirical method for appraising the fresh and salt-water exchanges which occur in an estuary.[1]

The technique was applied to the Patapsco Estuary to determine river-water accumulation within the Harbor for an assumed stream discharge. From this, the flushing or detention time of the Estuary could be calculated.

Ketchum reasons that the tidal excursion represents the maximum length over which mixing can logically be assumed. He defines consecutive volume segments within the estuary so that the distance between their inner and outer boundaries is equal to the average excursion of a water particle on the flooding tide. Through consideration of the age of river-water increments in any segment (n), he derives an expression for the total accumulation of river water (Q_n) within the segment, assuming steady state conditions (constant river flow):

$$Q_n = \frac{R}{r_n}$$

In this equation, r_n is the exchange ratio, defined as the ratio of intertidal volume to high-tide volume for the segment and R is the river flow during a tidal cycle. The total river-water accumulation within the estuary is obtained by addingthe amounts in each segment.

$$\sum_{o}^{n} Q_n = \sum_{o}^{n} \frac{R}{r_n}$$

Actual procedure in any instance first involves segmentation of the estuary from curves giving the low-tide, high-tide and tidal prism volumes against the length of the estuary for an assumed river flow. Successive segment boundaries are located so that the high-tide volume in any segment is equal to the low-tide volume in the adjacent seaward one; the distance between segment boundaries is then the average tidal excursion for that section of the estuary. From the volumes within each segment, exchange ratios and the accumulated river-water volume are computed; the sum of the latter is the total river-water accumulation within the estuary for the

[1] Ketchum, Bostwick H., The Exchanges of Fresh and Salt Waters in Tidal Estuaries, Proceedings of the Colloquium on the Flushing of Estuaries, Woods Hole Oceanographic Institution (1950), p. 1.

assumed conditions. Development of the hypothesis includes the fundamental assumption that the contents of each segment defined by the tidal excursion are completely mixed at high tide. Where field data for particular studies reveal incomplete mixing, suitable adjustments are indicated.

The dendritic plan of the Patapsco Estuary complicates the usefulness of this approach. Arbitrary application of the procedure to the Harbor *in toto* is unsatisfactory, for lateral mixing into peripheral sections is incomplete. Nevertheless, the large tidal prism volumes of locations such as Bear Creek, Curtis Bay and Middle and Northwest Branches must be included in any analysis. The most reasonable adjustment would appear to be treatment of these sections as tidal flats. On this basis, and assuming that vertical mixing in the fairway is effective to a depth of 18 ft., the river-water accumulation calculates to be 3.7×10^9 cu. ft. for a river flow of 400 cfs. A Harbor flushing time of 107 days is indicated for these conditions.

ANALYSIS OF HARBOR "BREATHING" MECHANISM

The effects of the gross changes in water surface elevation which occurred in Baltimore Harbor during the period Nov. 18-30, 1950, are shown in Table E-1. This table also shows the fraction of water present in the Estuary on Nov. 18 which remained after each date listed.

TABLE E-1

EXCHANGE OF HARBOR WATER DUE TO WATER LEVEL FLUCTUATIONS

Date	*Water surface condition**	*Water Volume***		*Per cent of original water remaining*
		Change	*Total*	
11–18–50	At Mean Low Water	....	15.4	100
11–20–50	Raised 2.5 ft. to Elev. +2.9	+2.7	18.1	100
11–21–50	Lowered 4.9 ft. to Elev. —2.0	—4.6	13.5	75
11–25–50	Raised 7.5 ft. to Elev. +5.5	+8.2	21.7	75
11–29–50	Lowered 6.2 ft. to Elev. —0.7	—6.9	14.8	51

* Elevations recorded on City tide gage, Pier 7, Northwest Branch. Readings in ft.

** Water volumes in billions of cu. ft. Positive and negative values for change represent inflow and outflow, respectively. Total is volume present in Harbor at end of changed water surface elevation.

Computations are based on the capacity curve for the Harbor, Fig. E-1, which was prepared by planimetering contour areas from 1/15,000 and 1/40,000 U.S.C.&G.S. charts and computing volumes by the average-end-area method. They include the simplifying assumptions 1) that banks at the shoreline are vertical above MLW., and 2) that the contents of the Estuary are mixed completely at the end of each major addition or loss of water.

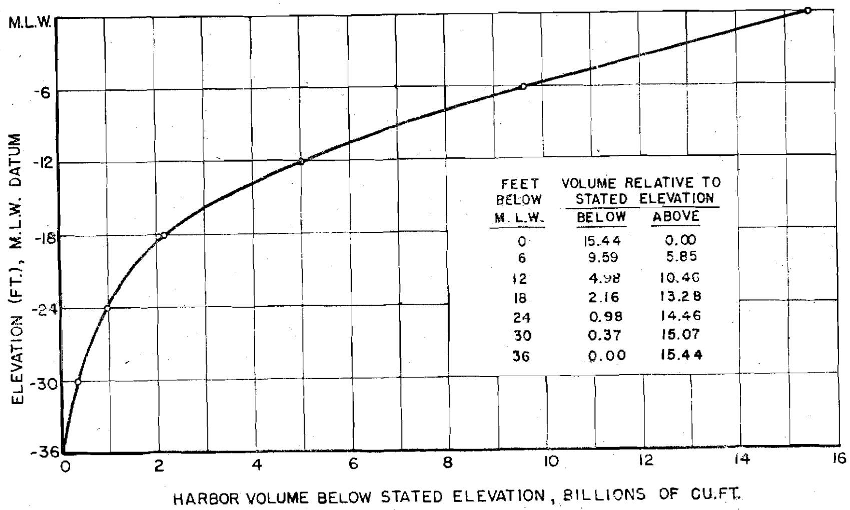

Fig. E-1.
Baltimore Harbor
CAPACITY CURVE

APPENDIX F.

RESULTS OF ANALYSIS OF BOTTOM MUD COLLECTED FROM BALTIMORE HARBOR

Analysis of Harbor bottom muds have been tabulated for use in this appendix but, because of their volume, consisting of eight full pages, the data are not reproduced here. Rather, these data are available in the original report now on file in the library of The Johns Hopkins University for study and use by interested workers.

The locations at which samples were collected are shown in Fig. F-1. Location code numbers listed in tabulated data refer to the arbitrary coordinate system appearing on this sketch.

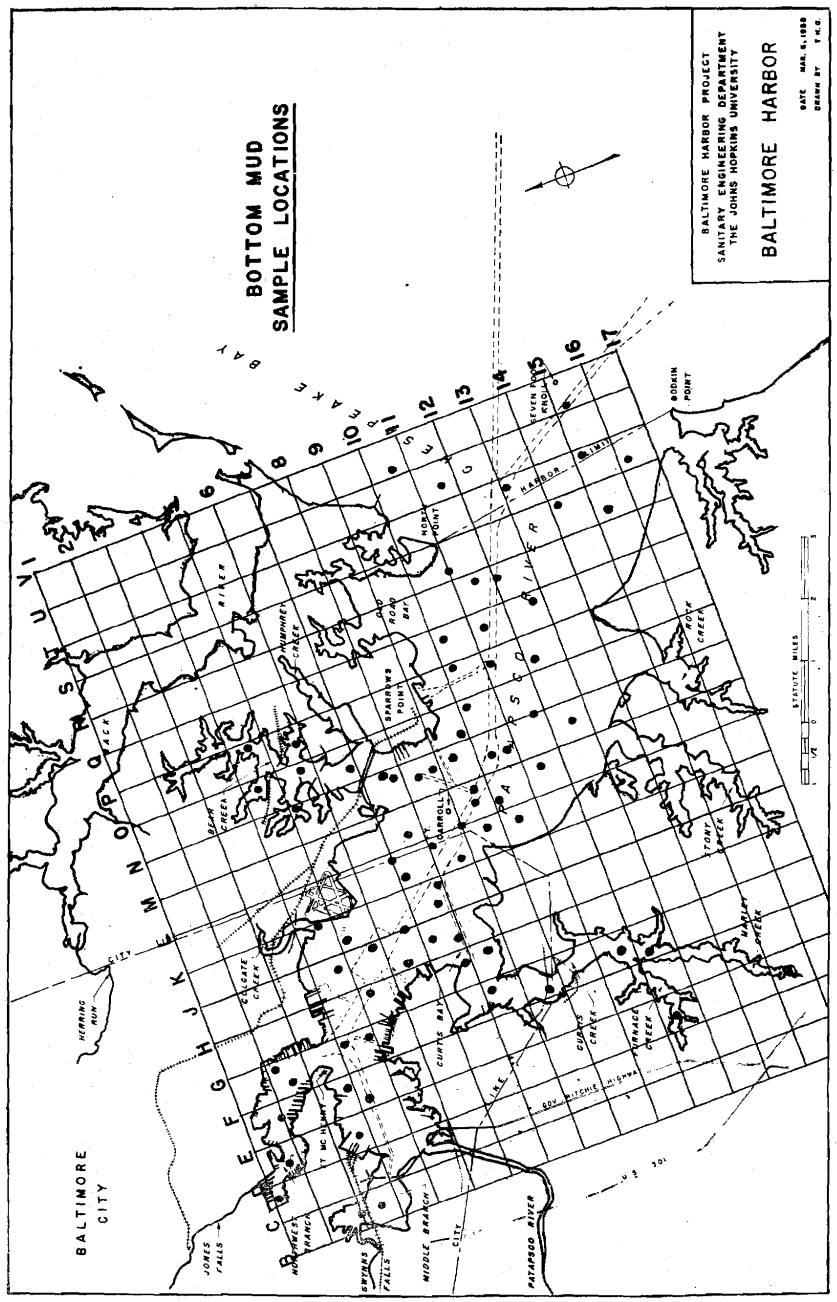
BOTTOM MUD
SAMPLE LOCATIONS
BALTIMORE HARBOR PROJECT
SANITARY ENGINEERING DEPARTMENT
THE JOHNS HOPKINS UNIVERSITY
BALTIMORE HARBOR
BALTIMORE CITY
PATAPSCO RIVER
STATUTE MILES

Fig. F-1.

APPENDIX G.

ANALYTICAL DATA FOR SURFACE AND BOTTOM WATER COLLECTED ROUTINELY FROM REGULAR SAMPLING STATIONS IN BALTIMORE HARBOR

This appendix contains the results of physical-chemical analyses of water collected routinely from Baltimore Harbor during the period 1947-49, but, because of their volume, consisting of fifty pages, the data are not reproduced here. Rather, these data are available in the original report now on file in the library of The Johns Hopkins University for study and use of interested workers.

Data are arranged chronologically by stations, the locations of which appear in Fig. 14 of the report. Surface samples were collected at a water depth of about one foot and are designated by the letter (T) after station numbers. Bottom samples were taken at a depth of 35 ft. or approximately one foot off the bottom, and are keyed by the letter (B) after station numbers. For example, data for surface samples collected at Station 5 are noted under Station 5-T. Those for bottom samples at the same location are listed under Station 5-B.

APPENDIX H.

RESULTS OF VERTICAL PROFILE SAMPLING OF BALTIMORE HARBOR WATER

This appendix contains the results of examination of Harbor Water collected at 5-ft. vertical increments, but, because of their volume, consisting of twenty-five full pages, the data are not reproduced here. Rather, these data are available in the original report now on file in the library of The Johns Hopkins University for study and use of interested workers.

Data are arranged chronologically by stations, the locations of which appear in Fig. 14 of the report. The depth in feet at which samples were collected is noted by the figure which follows station numbers. For example, Station 13-15 denotes the 15-ft. depth at Station 13. Surface samples (T) were taken at a depth of about 1 ft.