

Barry A Wade

THE POLLUTION ECOLOGY OF KINGSTON HARBOUR, JAMAICA

SCIENTIFIC REPORT OF THE U.W.I. - O.D.M.
KINGSTON HARBOUR RESEARCH PROJECT
1972 - 1975

VOLUME 1



BY
BARRY A. WADE

RESEARCH REPORT FROM THE ZOOLOGY DEPARTMENT
UNIVERSITY OF THE WEST INDIES, MONA
NUMBER 5
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VOLUME I

- PART 1. GENERAL INTRODUCTION
PART 2. WATER QUALITY
PART 3. OXYGEN BALANCE

By

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Research Report from the Zoology Department
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FOREWORD

This report is the result of work carried out on aspects of the pollution ecology of Kingston Harbour and has been made possible by a 3-year grant from the United Kingdom Ministry of Overseas Development to the University of the West Indies (Scheme R 2669). However, the report also includes data gathered in studies prior to the commencement of the ODM grant and financed by the University's Research and Publication Fund, as well as data obtained for the Government of Jamaica's Kingston Harbour Quality Monitoring Committee on which the author has served as Vice Chairman and supervisor of field work.

The report is bound in 3 Volumes as follows:-

Volume I:

- Part 1. General Introduction
2. Water Quality
3. Oxygen Balance

Volume II:

- Part 4. Benthic Ecology

Volume III:

- Part 5. Pollution Abatement and Harbour Improvement

The author is greatly indebted to the British and Jamaican Governments and the University of the West Indies for their financial and other support.

Professor Ivan Goodbody, Head of the Zoology Department, has enthusiastically supported this research throughout and I am grateful for his encouragement and advice.

(ii)

I have benefited much from discussions with my colleagues in the Zoology Department especially Dr. J. Grahame, Dr. E.S. Grahame and Mr. K. Deeming who have worked in Kingston Harbour, and with various Government officers who have served on the Kingston Harbour Quality Monitoring Committee.

Without the technical assistance from a number of persons, this work would not have been possible. I am particularly grateful to the following persons who have worked with me at one time or another: Mrs. Louise Antonio, Miss Gemma Deonarine, Mrs. Marilyn Robinson, Mr. Phillip Motta, Mr. Richard Hubbard and Mr. Paul Hewling.

Mr. Herman Murphy, Mr. George Hamilton and other persons at the Port Royal Marine Laboratory have given invaluable help in the field work, for which I am grateful.

Valuable unpublished data and technical assistance have been provided by the Government Meteorological Office, the Scientific Research Council and the Government Medical Laboratory.

The illustrations were prepared by Mrs. Avril Chang and Mrs. Elaine Fisher, to whom I record my thanks.

Dr. Peter Wickstead, Professor Ivan Goodbody and colleagues in the Zoology Department kindly reviewed the manuscript and offered much useful criticism.

Finally, my deep appreciation is due to Mrs. Patricia Wade for her untiring effort and patience in typing the report.

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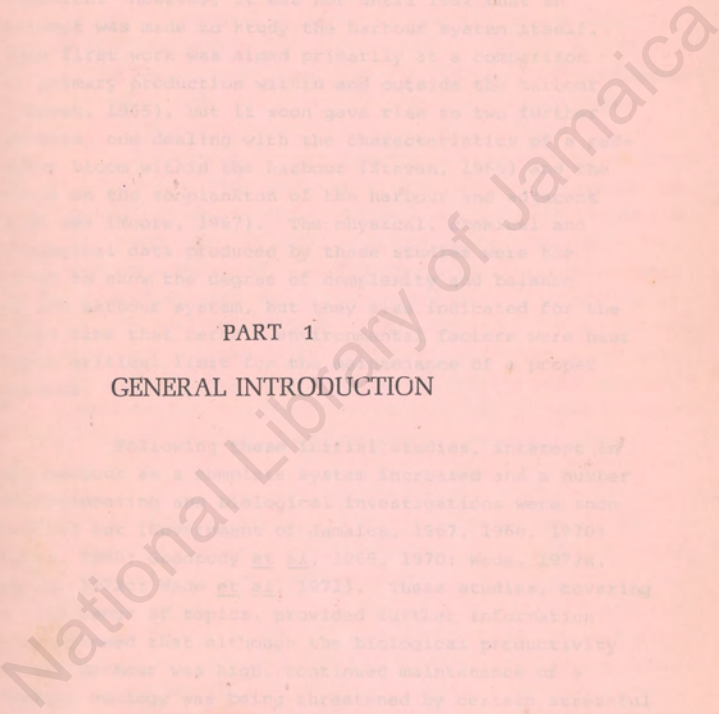
1. HISTORICAL REVIEW

Ever since the University of the West Indies established its marine laboratory at Port Royal in 1955, Port Royal Harbour has been the center for much ecological research. However, it was not until 1967 that an attempt was made to study the harbour system itself. The first work was aimed primarily at a comparison of primary production within and outside the harbour (Stevan, 1965), but it soon gave rise to two further studies, one dealing with the characteristics of the water column within the harbour (Stevan, 1966) and the other on the zooplankton of the harbour and the coast (Stevan & Moore, 1967). The physical, chemical and biological data produced by these studies were the first to show the degree of degradation of the harbour system, but they also indicated for the first time that the harbour facilities were near their critical limit for the occurrence of a proper ecological system.

PART 1

GENERAL INTRODUCTION

Following these initial studies, interest in the harbour as a complex system increased and a number of other biological investigations were soon carried out (Department of Jamaica, 1967, 1968, 1970; Gentry, 1968; Gentry *et al.*, 1968, 1970; Wade, 1970a, 1970b; Gentry *et al.*, 1971). These studies, covering a wide range of topics, provided further information on the harbour system and its biological productivity. It was found that although the biological productivity of the harbour was high, continued maintenance of this high level was being threatened by certain adverse conditions. Some of these conditions and the factors causing them were discussed by Gentry (1968, 1971), Gentry *et al.* (1970), Wade (1970a, 1971a)



1. HISTORICAL REVIEW

Ever since the University of the West Indies established its marine laboratory at Port Royal in 1955, Kingston Harbour has been the center for much ecological research. However, it was not until 1962 that an attempt was made to study the harbour system itself. This first work was aimed primarily at a comparison of primary production within and outside the harbour (Steven, 1965), but it soon gave rise to two further studies, one dealing with the characteristics of a red-water bloom within the harbour (Steven, 1966) and the other on the zooplankton of the harbour and adjacent open sea (Moore, 1967). The physical, chemical and biological data produced by these studies were the first to show the degree of complexity and balance of the harbour system, but they also indicated for the first time that certain environmental factors were near their critical limit for the maintenance of a proper balance.

Following these initial studies, interest in the harbour as a complete system increased and a number of engineering and biological investigations were soon carried out (Government of Jamaica, 1967, 1968, 1970; Munro, 1968; Goodbody et al., 1969, 1970; Wade, 1972a, 1972b, 1972c; Wade et al., 1972). These studies, covering a wide range of topics, provided further information which showed that although the biological productivity of the harbour was high, continued maintenance of a healthy ecology was being threatened by certain stressful conditions. Some of these conditions and the factors causing them were discussed by Goodbody (1968, 1970), the Government of Jamaica (1970), Wade (1972b, 1972c)

and Wade et al (1972) in a series of publications describing the state of the harbour and seeking to draw attention to the need for positive action for the preservation of a healthy harbour environment. The effect of these publications began to be realised in 1970 when various grants began to be made available to the University of the West Indies for conducting further investigations of the harbour with a view to making recommendations for improving its condition. Since then, the following studies have been performed: a study of physical conditions and water movement (principal investigator - K. Deeming, 1970 - 1972); a study of zooplankton (principal investigator - J. Grahame, 1970 - 1973); a study of phytoplankton (principal investigator - E.S. Grahame, 1971 - 1973); and a study of soft-bottom communities and oxygen balance (principal investigator - B. Wade, 1972 - 1975). At the same time since 1970, the Government of Jamaica through its Kingston Harbour Quality Monitoring Committee, has been monitoring certain water quality parameters at fortnightly or monthly intervals at a number of stations throughout the harbour.

The present report is the result of work carried out primarily on the soft-bottom communities and has been made possible by a 3-year grant from the United Kingdom Ministry of Overseas Development to the University of the West Indies. However, this report also includes data on the benthos collected in studies prior to the commencement of this grant in 1972 and funded through the University's Research and Publication Fund.

A major section of the report is also devoted to a discussion of the water quality characteristics of Kingston Harbour based on data collected for the Government Monitoring Committee on which this author has served since its commencement, as well as on independent studies conducted by this author under the O.D.M. Grant. Another major section is further devoted to a discussion of oxygen balance in the harbour.

Of the four principal studies conducted by the U.W.I. since 1970, the report of only one, the zooplankton, has been completed to date (Grahame, 1974). At the time of writing, all the others are in preparation. Nevertheless, as this is likely to be the last in the series to appear, it seems desirable to attempt an overall synthesis of the results of these studies and to make recommendations for arresting pollution in the harbour and improving conditions. As a result, it is necessary in this report to discuss the presently unpublished work of my colleagues and to draw certain conclusions based on them. While I do this with their permission and am happy to acknowledge their contributions, total responsibility for accuracy of the information rests with me and the conclusions and recommendations I make must be regarded as my own.



Figure 1

Kingston Harbour, showing its location
and major features.

KINGSTON HARBOUR

- 3 --- 3 fathom contour
 --- 6 --- 6 fathom contour

2. DESCRIPTION OF KINGSTON HARBOUR

2.1 The Area

Kingston Harbour is a semi-enclosed bay situated on the south coast of Jamaica at latitude $17^{\circ} 57' N$ and longitude $76^{\circ} 48' W$ (Fig. 1). It is bounded on the north, east and west by the mainland coast and on the south by a narrow spit of land, the Palisadoes. The entrance to the open sea is by a 3.2 km (2 mile) wide channel at the southwest corner. The harbour extends approximately 16.5 km (10.3 miles) in an east-west direction and between 2.7 and 6.5 km (1.7 & 4.1 miles) in a north-south direction. The total area is more than 51 square kilometers (19.9 sq. miles).

The city of Kingston with a population of over 600,000 persons occupies all of the northern shore of the harbour while a new suburban housing area with about 60,000 persons is developing rapidly on the western shore. The Norman Manley International Airport is situated midway along the Palisadoes spit while the small town of Port Royal is located on its western tip at the entrance to the harbour.

2.2 Physiography

Kingston Harbour consists of three main regions, the Inner Harbour, the Outer Harbour and Hunts Bay (Fig. 1). The Inner Harbour is comprised mainly of a deep basin which slopes gradually from a depth of about 12 m (40 ft.) in the west to 18.3 m (60 ft.) in the east. Goodbody (1970) has proposed the name Upper Basin for the eastern end of the Inner Harbour.

The Inner Harbour is connected with the Outer

Harbour by a narrow ship channel of about 12 m (40 ft.) depth. The Outer Harbour itself is mainly a deep basin which slopes gradually from the depth of the ship channel down to a maximum of about 18.3 m (60 ft.) near the entrance to the harbour.

Hunts Bay is a shallow basin with an average depth of about 2.4 m (8 ft.). Most of its area was cut off from the rest of the harbour in 1969 by the construction of a solid-fill causeway with a narrow opening of only 213 m (700 ft.).

The southern section of the Inner Harbour west of the airport comprises extensive sand shoals and mangrove swamps with depths from 0.3 m (1 ft.) to 5.5 m (18 ft.). It is these shoals and swamps which effectively separate the Inner Harbour basin from that of the Outer Harbour. The western section of the Outer Harbour also comprises sand shoals and since 1970, it has been connected with an enclosed mangrove lagoon, Dawkins Pond, by the creation of a boat channel through the barrier sand spit.

The two deep basins and Hunts Bay have soft mud bottoms made up of silts and clays while the sand shoals are covered by bare patches of fragmented remains of coralline algae, especially Halimeda, and meadows of the turtle grass, Thalassia. The Government of Jamaica (1968) report on Kingston Harbour has provided a distribution map of bottom material in the harbour.

Fresh water enters the harbour at Hunts Bay by two rivers, the Rio Cobre and the Duhaney and by a drainage scheme, the Sandy Gully, as well as along

the northern shore by way of several intermittent gully streams (Fig. 2). It has been estimated that 662 square kilometres (256 sq. miles) of land drain directly into Hunts Bay while only 52 square kilometres (20 sq. miles) drain directly into the Inner Harbour. The most important source of freshwater is the Rio Cobre which, however, has a highly variable flow. Its mean discharge has been estimated at 6.2 cubic metres per second (219 cubic feet per second), but during flash floods especially in October, peak flow may rise to $283 \text{ m}^3/\text{sec}$ (10,000 cfs). On the other hand the Duhaney River maintains a fairly uniform discharge throughout the year and has an average flow of about $2.83 \text{ m}^3/\text{sec}$ (100 cfs) or less than a half that of the Rio Cobre. The discharge rate of the Sandy Gully over a one year period has been estimated at 61,317 million litres (13,500 million gallons) or the equivalent of $1.9 \text{ m}^3/\text{sec}$ (68.3 cfs) while that of all the remaining gullies on the north shore is 54,504 million litres (12,000 million gallons) a year or $1.7 \text{ m}^3/\text{sec}$ (60.7 cfs) equivalent (Government of Jamaica, 1970).

The tide in Kingston Harbour is semidiurnal when the moon is over the equator and becomes diurnal during maximum north and south declinations of the moon. Highest tides are 0.456 m (1.5 ft.), the mean range is 0.234 m (0.77 ft.) and the extreme range is 0.882 m (2.90 ft.).

Winds in the days are mostly sea breezes from the east south east and south east and are invariably more than 10 knots. On the other hand, night breezes off the land are from the north or north north west and

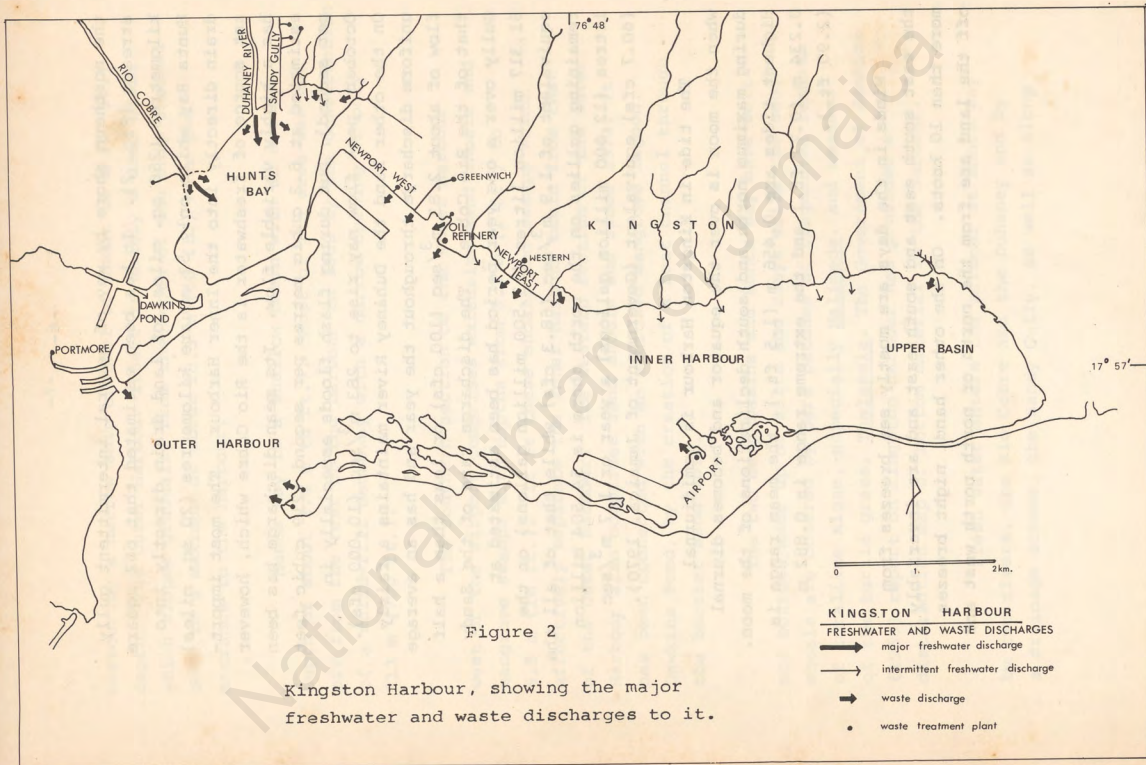


Figure 2

Kingston Harbour, showing the major freshwater and waste discharges to it.

- KINGSTON HARBOUR**
FRESHWATER AND WASTE DISCHARGES
- ▶ major freshwater discharge
 - ▶ intermittent freshwater discharge
 - ▶ waste discharge
 - waste treatment plant

are typically less than 10 knots. The windiest time of the year is March to August. There is a rapid fall-off during October resulting in the last three months of the year being much less windy.

The sea breezes create high wave action during the day and are responsible for vertical mixing of the water column. Furthermore, the winds appear to be primarily responsible for a seiche along the harbour having a period of 45 to 60 minutes and an amplitude of 5 to 7.5 mm (2 to 3 inches) (Government of Jamaica, 1968).

Currents in the harbour are generally weak and less than 30.5 cm/sec. (1 ft./sec.) except in certain narrow channels. The Government of Jamaica Report (1968) indicated that the principal currents were tide generated and were comprised of simple ebb and flood movements in and out of the system with rise and fall of the tides; bottom and surface currents were essentially similar. However, Goodbody (1970) has pointed out that the Government survey was conducted during a period of calm and the absence of wind and did not take into account the possibility of wind driven currents occurring at other times of the year. He has presented arguments to show that in fact wind driven currents may override the tidal effect in surface waters and that during periods of heavy winds when surface waters are being moved from the eastern end of the harbour towards the west, bottom currents moving in the opposite direction could be set up to form a counter flow. Goodbody's hypothesis has since been confirmed and the significance of these currents will be considered under the discussion of water quality.

Since the Government of Jamaica study of 1968, the Hunts Bay causeway has been constructed and it has had a considerable effect on the water movements in that area. In the first place, wave action in the enclosed bay has been greatly reduced due to a reduction in wind fetch. Secondly, ebb and flood tide currents have been restricted to the narrow opening and have consequently increased in strength. Thirdly, the increase in velocity of the ebb current has produced a jet effect so that the Hunts Bay water now spouts out much farther into the Inner Harbour than previously, thus further modifying the currents in that area. There is some speculation that this might be resulting in siltation of parts of the shipping lane.

2.3 Biology

The outstanding feature of the biology of Kingston Harbour is its high primary productivity, especially in the Inner Harbour. Steven (1965) measured the productivity of the Inner Harbour by phytoplankters to be about forty times that of the open ocean south of Kingston and showed that this difference could be correlated with differences in the amounts of dissolved nutrients (nitrates, nitrites, phosphates, silicates) present in the water outside and inside the harbour. He concluded that the gradient of primary production from outside to inside the harbour "appears to be generally independent of climatic or other obvious external factors and can be presumed to be internally self-maintaining, probably by local recycling of nutrients."

Steven's conclusions on high productivity in the harbour have been supported by E.S. Grahame's (personal communication) work on the phytoplankton and by Moore's (1967) and J. Grahame's (1974) studies of zooplankton abundance. However, J. Grahame has shown that the harbour supports not one but at least four distinct communities of zooplankters, all of high standing crop. These are an Outer Harbour community, a Hunts Bay community, an Inner Harbour community, and an Upper Basin community. Furthermore, he has concluded that components of these communities show responses to physical factors, especially to local rainfall and run-off via the Rio Cobre, but that these responses are probably mediated through the phytoplankton. Similarly, E.S. Grahame has found a number of distinct phytoplankton communities in the harbour, with fresh-water dilution playing a significant role in determining the species composition, especially in Hunts Bay. Hence, the picture we have of plankton production in the harbour is of high nutrient concentrations supporting large standing crops of distinct communities in various parts of the harbour with freshwater appearing to be a major factor in determining their composition.

The high nutrient levels and primary production in the harbour have given rise to eutrophic conditions, especially in the Inner Harbour and Hunts Bay. This has been evidenced by the increasing occurrence of phytoplankton blooms (Steven, 1965; Wade, 1969; Grahame, 1974) and by the tendency for subsurface waters to be deficient in oxygen (Wade et al, 1972; Grahame, 1974). Wade et al (1972) have

shown that benthic populations have suffered from these conditions while, on the other hand, Grahame (1974) has shown that the zooplankton thrive by them.

In addition to the production by planktonic organisms, Kingston Harbour also supports high primary production in the turtle grass beds and mangroves. Goodbody (1970) has estimated that there are 809 hectares (2,000 acres) of turtle grass in the harbour and Greenway (1974) has measured a production rate of 2165 g dry weight/m² per year for the shoots of this species. Hence, if all the turtle grass in the harbour beds were to maintain this level of production, total production of organic matter by the shoots would be an incredible 752×10^6 g/yr. It is unlikely, however, that all the beds would maintain the level of production measured by Greenway due to lower densities and reduced light etc. Nevertheless, since her measurement relates to organic matter in the shoots only and does not take into account the amount stored in the rhizomes, we could safely estimate the total production to be of the order calculated above. However, how all this organic matter is utilised in the harbour and what role it plays in the energetics of the system still remain to be solved.

The rate of primary production by mangroves in Kingston Harbour has not been measured, but it is believed to be high. However, as Goodbody (1974) has pointed out, the total area of mangroves in the harbour has been reduced by less than half in recent years due to clearance and, if the trend continues, the mangroves could lose their importance as primary producers in the system. Nevertheless, the Port Royal mangrove swamp

continues to harbour a rich and diverse sessile fauna and commercial oyster exploitation is carried out on a minor scale (Siung, 1976).

The benthic communities of Kingston Harbour have been described in a number of publications by Wade (1972a, 1972b) and Wade et al (1972), and the effect of deficient oxygen levels on them have been discussed. It has been shown that in 1968, there were 5 distinct bottom communities in the harbour - two in the Inner Harbour basin, one in Hunts Bay, one in the Outer Harbour basin, and one on the sand shoals. These showed a pattern of increased diversity as one moved from the Inner Harbour and Hunts Bay out to the Outer Harbour. However, due to oxygen deficiency, both Inner Harbour communities and the Hunts Bay community began to deteriorate with the result that by 1972, one of the Inner Harbour communities had completely disappeared, the other had shifted westward and the Hunts Bay community had undergone very substantial changes. Accompanying all these was the creation and spread of an abiotic zone in the Inner Harbour. Up to 1972, the community of the Outer Harbour which had been described as one of the most diverse in the world had not seemed to have undergone much change. However, this report will take up the story of the benthos again and will describe further effects on all the communities since 1972. In short, the trend which had been observed up to 1972 has continued and all of the benthos now show the unmistakable effects of environmental stress.

Publications on the fish and shrimp populations of Kingston Harbour are few. Munro (1968) in a

trawl survey of the harbour found that there were sufficiently large populations of demersal fish and shrimp in the harbour to justify the creation of a small-scale trawling industry in the Inner Harbour. However, this author has observed that these populations have disappeared from the Inner Harbour along with the benthos.

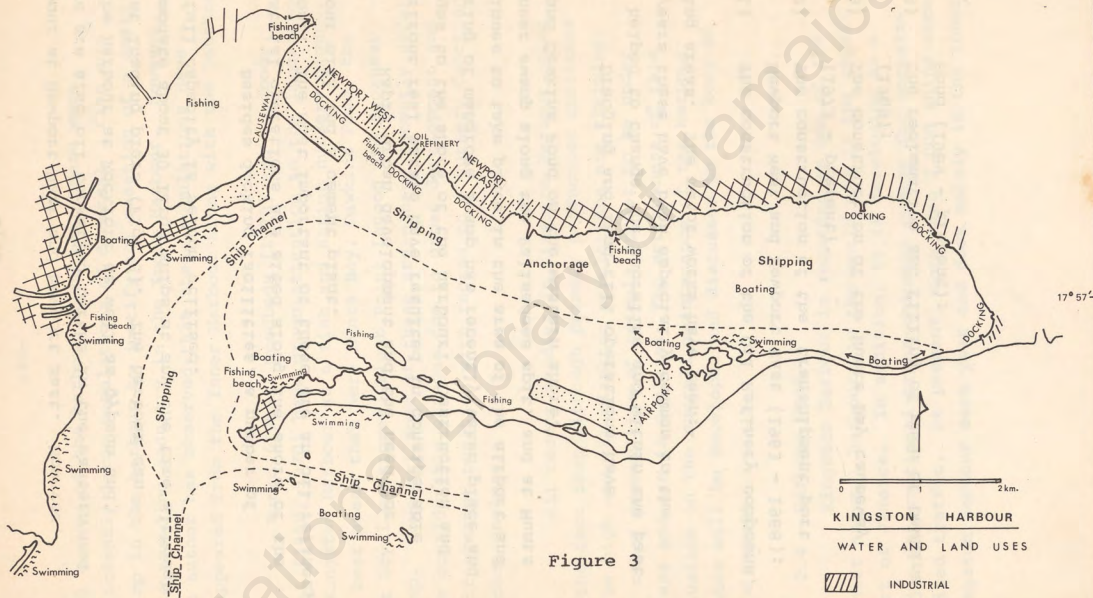
Munro (1968), Goodbody (1970) and Goodbody et al (1969, 1970) have drawn attention to the importance of Kingston Harbour as a fish and shrimp nursery ground. The best areas then were Hunts Bay, Dawkins Pond, the Port Royal mangroves, Plumb Point Lagoon and Buccaneer Swamp. However, some of these areas have recently undergone considerable changes due to urban development and their present position with regard to a nursery function is thus unclear.

All recent studies in Kingston Harbour point to the fact that although primary production continues to be high and the plankton populations are thriving, all other communities of animals appear to be under stress and are in decline. The seriousness of this situation on the overall maintenance of the harbour system will be developed and discussed in the body of this report.

2.4 Harbour Uses

Kingston Harbour is regarded as one of the finest natural harbours in the world and is the chief port of Jamaica. In addition, it is developing as a major international trans-shipment center for containerised traffic. At present, more than 2,000 ships enter Kingston Harbour each year and dock mainly in the Inner

76° 48'






17° 57'

Figure 3

Kingston Harbour, showing water
and land uses.

KINGSTON HARBOUR

WATER AND LAND USES

-  INDUSTRIAL
-  COMMERCIAL AND RESIDENTIAL
-  RECLAMATION AND FILL

Harbour at Newport West and Newport East. However, there are also oil bunkering berths in the eastern end of the harbour at Rockfort as well as gypsum and cement loading piers (Fig. 3). The harbour can accommodate about 30 large ships at any one time although its full capacity is seldom utilised.

Besides docking facilities, a number of industrial operations are sited along the shore of the harbour. The most important of these are an oil refinery, a flour mill and a cement plant.

Rapid urban development and the need for waterfront real estate have resulted in considerable changes to the shore of the harbour. Destruction and clearing of mangrove swamp has recently taken place and continues to take place in the area of the airport and Bucaneer swamp along the Palisadoes spit, and at Hunts Bay and Dawkins Pond on the western shore.

Dredging and land-fill operations have also helped to change the shoreline and within the past ten years these have been especially common in the docking areas. The major works have been:-

- 1) The construction of the Oil Refinery compound, Newport West and Newport East (1963 - 1968);
- 2) The construction of the transhipment port (1973 - present).
- 3) The construction of the Hunts Bay causeway (1969);
- 4) The reclamation and filling of much of Dawkins Pond (1969 - present);

- 5) The construction of a navigable channel linking Dawkins Pond and the Outer Harbour (1970); and
- 6) Filling of the shore adjacent to the cement factory (1965 - present).

Further changes including the extension of the airport runway and the creation of one or more causeways are also proposed.

Up until recently mud was dredged from Hunts Bay on a regular basis for the cement factory. This has now ceased, but there have been recent proposals to mine sand and gravel from parts of Hunts Bay and the harbour shoals for use in the building industry.

Despite the decline of fish populations and the destruction of valuable nursery grounds, Kingston Harbour is still a major fishing centre and forms the basis of livelihood for more than two thousand persons. Most importantly, it is a source of fry and shrimp bait for the offshore fishery. Up to recently a moderate oyster fishery based on the Hunts Bay and Dawkins Pond mangrove oysters was carried out, but with the destruction of these mangroves, this has ceased. Oysters are now only collected from the Port Royal mangroves, and the yield is much less.

Kingston Harbour is the most intensively used recreational facility in Jamaica and offers the greatest range of attractions of any single environment in the island. There are three public beaches and several private beaches, including those of two hotels,

along its shore; there are also three pleasure boat marinas, and a number of lay-by ramps for launching small boats and fishing. Swimming, skiing, sailing, line fishing and taking scenic boat rides are the popular attractions, which, according to one author, provide Kingston Harbour "the opportunity to develop into a very significant tourist playground" (Riley, 1969).

One of the very first marine laboratories in the Caribbean was established at Port Henderson along the shore of Kingston Harbour in the 1890's, because of the rich diversity of environments and biota which the harbour provided. Since then and especially after the establishment of the University's marine laboratory at Port Royal in 1955, the harbour has been used as a major centre of scientific research and instruction in the Caribbean. Indeed, the location of the University's laboratory on the shore of Kingston Harbour is widely regarded as one of the finest in the world for marine research.

All these uses and activities associated with Kingston Harbour help to make it one of the most valuable multi-purpose resources in Jamaica and are in no small measure responsible for the city of Kingston having developed into one of the largest industrial, commercial and residential centres in the Caribbean.

2.5 Pollution

Kingston Harbour receives a considerable amount of waste discharges from a number of sources.

The most important of these are stormwater run-off via rivers and gullies, sewage treatment plants, industrial outfalls and merchant ships. The Government of Jamaica (1970) in its report on a sewerage study for the City of Kingston estimated that the total pollution load to the harbour in terms of organic wastes was approximately 26,000 pounds of Biochemical Oxygen Demand (B.O.D.) per day. Of this amount, stormwater run-off accounted for about half the load while sewage and industrial wastes accounted for almost all the rest; the organic load from ships was negligible.

The volume of stormwater run-off reaching Kingston Harbour has probably remained the same order of magnitude for the past several years although it is conceivable that recent increases have occurred with urban build-up. However, the sewerage report does not predict any major increase in stormwater run-off for the next 35 years, and in fact suggests that the organic load from this source could be reduced as the gullies become cleaned up and stormwater is controlled. It should be pointed out here that gullies are at present a major avenue for solid and liquid waste disposal in the city and that any recent increases in their pollution load are most likely to be due to these activities than to increased flow per se.

There are at present no less than 15 sewage treatment plants which discharge their effluents either directly or by way of short water courses into the harbour (Table 1, Figure 2). Of these, the two largest are primary treatment plants, being the Western Plant (3.5 million gallons a day capacity), and the Greenwich Plant

Table 1: List of Sewage Treatment Plants which discharge to Kingston Harbour (Government of Jamaica, 1970)

Plant	Treatment	Capacity	Discharge
Eastern	Primary settling	3,500,000 gpd	Direct to harbour.
Greenwich	Primary settling	5,000,000 gpd	Direct to harbour.
Portmore	Extended aeration	416,000 gpd	Direct to Dawkins Pond.
Independence City	Extended aeration	416,000 gpd	Direct to Hunts Bay
Remo Ltd.	Extended aeration	33,000 gpd	To harbour via Duhaney River.
Duhaney	Contact stabilisation	834,000 gpd	To Duhaney River via creek.
Ughenden	Contact stabilisation	208,000 gpd	To harbour via Sandy Gully.
Prince Pen	Extended aeration	200,000 gpd	To harbour via Sandy Gully.
Kingston Wharves	Extended aeration	13,300 gpd	Direct to harbour.
Edde's Grant	Extended aeration	3,300 gpd	To harbour via gully.
Merger	Extended aeration	3,300 gpd	To harbour via Sandy Gully.
Paper Processors Ltd.	Extended aeration	6,250 gpd	To harbour via Sandy Gully.
Palisadoes Airport	Extended aeration	100,000 gpd	Direct to harbour.
Port Royal Police	Extended aeration	4,160 gpd	Direct to harbour.
PDF - Port Royal	Extended aeration	6,250 gpd	Direct to harbour.

* Since this list was compiled, a few other small plants have gone into operation.

(5.0 mgd capacity). All the rest are secondary plants. The Government of Jamaica study (1970) estimated the combined flow from these primary plants at the time to be approximately 4.6 mgd. However, flow of the Greenwich plant has more than doubled since then and their combined volume is now about 7.0 mgd.

Of the remaining plants, the estimated flow in 1970 was 1.75 mgd. However, this too has increased and is approximately double that today. Hence the total volume of sewage effluent reaching Kingston Harbour is now estimated to be 10.5 mgd.

The Government study estimated the total organic load to the harbour from sewage in 1970 to be 7,100 pounds B.O.D. per day. With the increased flows, this load is probably now about 12,600 pounds B.O.D./day.

Ships which enter Kingston Harbour are required to hold their sanitary wastes in tanks until after they have cleared port. However, the smaller cargo ships often do not have such tanks and may discharge raw sewage into the harbour. This practice appears to be declining as more ships are equipped with tanks and the problem does not seem too great.

In 1967, the Government of Jamaica conducted a bacteriological survey of the harbour to determine the extent of bacterial pollution. Their report showed that at that time, the entire northern shore of the Inner Harbour and Hunts Bay as well as along sections of the Palisadoes and Port Royal had coliform counts which were in excess of 2,400 MPN/100 ml or well above the limit

regarded as safe for human contact (Fig. 4). Hence, the report concluded that "in view of the bacterial pollution indicated by this survey, waters along the north shore and waterfront of Port Royal present an almost certain health hazard to bathers." However, no action has been taken to regulate or control bathing in these areas.

More recent bacteriological investigations carried out at the commencement of this project in 1972 and in 1973 have shown that the pattern of bacterial pollution has not altered much and, if anything, more areas are now being affected by sewage. Of particular interest is a high coliform level of 900 MPN/100 ml measured at Bucaneer Beach on the south shore of Kingston Harbour and a similar reading in Dawkins Pond. Since both of these places are in recreationally intensive areas and were previously free from bacterial pollution it should be of concern that the pollution resulting from sewage discharges should now have spread into these areas as well.

The 1970 Government study on sewerage estimated that wet industries in the city of Kingston generated approximately 2.1 mgd of waste, most of which were discharged to the Inner Harbour or Hunts Bay. The total B.O.D. load of these wastes was further estimated at 7,000 lbs./day, or approximately the same as the sewage load at the time. The types of industries, the volume of their effluents and the nature of the wastes at that time are given in Table 2. However, these have also increased since the survey.

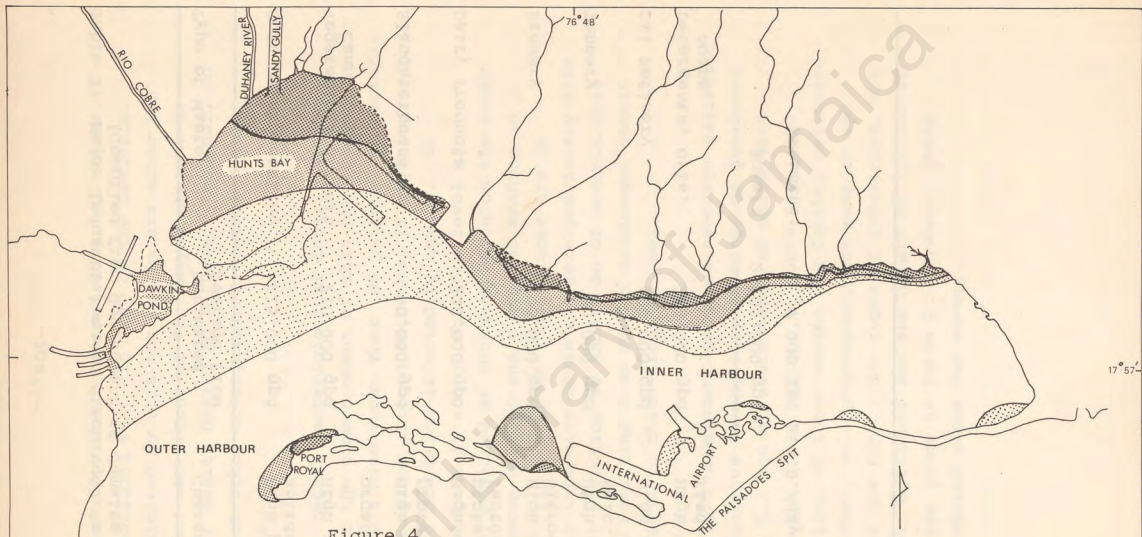


Figure 4

Bacterial levels in Kingston Harbour as determined by a Government of Jamaica Survey in 1967 and further measurements by the author in 1972 - 73.

-----edge of harbour in 1967

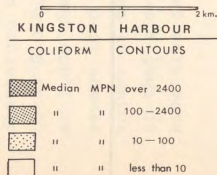


Table 2: Major industrial wastes discharged to Kingston Harbour
(Compiled from Government of Jamaica Report, 1970)

Type of Waste	Estimated Average Flow	Characteristics
Soft Drink Bottling	225,000 gpd	High pH, suspended solids, B.O.D.
Vegetable and Fruit Canning	210,000 gpd	High suspended solids, and dissolved organic matter.
Slaughterhouse	90,000 gpd	High organic matter, proteins, fats.
Dairy Products	200,000 gpd	High organic matter, proteins, fats and lactose.
Brewery	700,000 gpd	High dissolved organics, nitrogen and starches.
Tannery	30,000 gpd	High solids, hardeners, salt, pH and B.O.D.
Oil Refinery	400,000 gpd	High B.O.D.
Detergents, Oils, Soaps	250,000 gpd	High B.O.D. and saponified soaps.
Total:	2,105,000 gpd	
Estimate:	7,000 lb. B.O.D./day	

The high organic loading reaching Kingston Harbour by stormwater, domestic sewage and industrial wastes has helped to create a condition of oxygen deficiency throughout most of the harbour. Wade et al (1972) have described the nature of this organic pollution and have discussed its effect on benthic communities in a preliminary manner. However, this subject will be taken up again at some length later in this report, and will not be discussed further at this time. Similarly, the problem of eutrophication already mentioned, resulting from nutrient input by way of stormwater, sewage and industrial wastes will also be considered later.

In addition to the organic and nutrient inputs, a number of other pollutants enter Kingston Harbour. Of great importance are heavy metals and pesticides, both of which seem to be in high concentrations in Hunts Bay. Unfortunately, however, although some preliminary screening for these pollutants has taken place, no published information is available.

Oil pollution from ships in Kingston Harbour is increasing due to the discharge of oil contaminated bilge and ballast water at nights by smaller ships which do not have their own oil separation equipment. These discharges result in the formation of extensive slicks which, under the influence of land breezes at night, are transported over to the south shore of the harbour where they frequently foul recreational facilities at Gunboat Beach, Bucaneer Beach, the Yacht Club and Morgan's Harbour. Fortunately, however, no really large spills have occurred either intentionally or by accident.

The final form of pollution in Kingston Harbour , and the most visible, is that caused by solid waste disposal. There are three main causes. First is the dumping of wastes in the land-fill areas, notably along the Hunts Bay causeway and the cement factory fill. Second, is the dumping of garbage in gullies, which, during rains, discharge their contents into the harbour. And third, is the disposal of refuse from ships. None of these disposal practices is legal, and it should therefore not be difficult to control them by enforcing the laws. However, the result of this present lack of enforcement is a significant fouling of the harbour water and a consequent reduction in aesthetic appeal.

The extent of pollution in Kingston Harbour may be determined by examination of certain water quality parameters. Such an examination, together with a discussion of the factors affecting water quality, form the basis of Part 2 of this report.

3. SUMMARY

(1) Kingston Harbour, situated on the south coast of Jamaica, is a semi-enclosed body of water which has only a narrow channel connecting it with the open sea. It comprises three main regions, the Inner Harbour, the Outer Harbour, and Hunts Bay and occupies approximately 51 square kilometres (19.9 square miles). The city of Kingston and its suburbs, with a population of nearly 700,000 persons is situated on its northern and western shores.

(2) The harbour is a physiographically complex system which, historically, has maintained fairly stable conditions of shape, depth and water characteristics. However, within the past 20 years, man-made changes have occurred such as the removal of mangrove swamps, the reclamation of low-lying areas, river and drainage diversions, dredgings, fillings and the construction of a causeway. These activities have served to alter the stability of the harbour in a number of ways although this is not yet fully understood. Nevertheless, there is evidence that the system is presently in the process of readjustment to these altered conditions.

(3) The outstanding feature of the biology of Kingston Harbour is its high primary production. However, recent studies indicate that although primary production remains high and plankton thrive in the harbour, all other animal communities appear to be under stress and are in decline. This is especially evident in the demersal fish and benthic invertebrate communities which, in the past ten years or so, have largely disappeared from the Inner Harbour and Hunts Bay.

INTRODUCTION

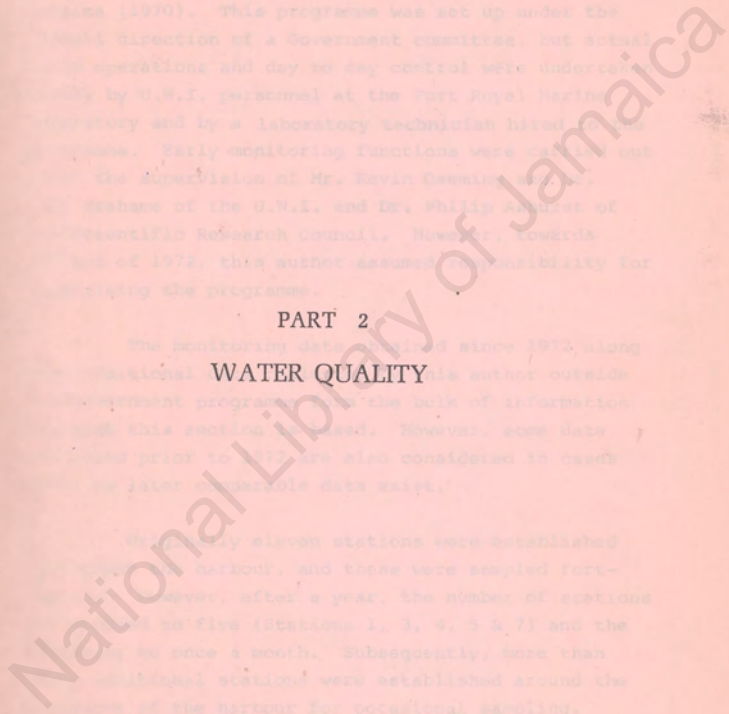
Early in 1971 the Government of Jamaica established a water quality monitoring programme in Port Antonio Harbour as a result of recommendations made in the sewerage study report of the Government of Jamaica (1970). This programme was set up under the overall direction of a Government committee, but actual day to day operations and day to day control were undertaken by U.W.I. personnel at the Port Royal Marine Laboratory and by a Laboratory Technician hired for the purpose. Daily monitoring functions were carried out under the supervision of Mr. Kevin Desmaris, a Senior Research Officer of the U.W.I. and Dr. Philip August of the Scientific Research Council. However, towards the end of 1972, this author assumed responsibility for operating the programme.

PART 2

WATER QUALITY

The monitoring data collected since 1972, along with occasional data collected by the author outside the Government programme, form the bulk of information used in this section. However, some data collected prior to 1972 are also considered in cases where no later comparable data exist.

Originally eleven stations were established around the harbour, and these were sampled fortnightly. However, after a year, the number of stations was reduced to five (Stations 1, 3, 4, 5 & 7) and the sampling frequency was reduced to once a month. Subsequently, more than a dozen additional stations were established around the perimeter of the harbour for occasional sampling. This section gives the locations of all these water quality monitoring stations.



(4) Kingston Harbour is a valuable multi-purpose resource, and the success of Kingston as a city has to a large extent been dependent on it. In the first place, it is one of the finest natural harbours in the world, and, in addition to being the center of the island's sea trade, is rapidly developing as a major international transshipment port. Secondly, it has been and remains the largest fishing center in the island despite the recent decline in fish and shellfish populations. And thirdly, it is the most intensively used recreational facility in Jamaica, providing not only a wide range of enjoyment for residents, but also offering opportunities for the development of a variety of tourist attractions.

(5) The present and potential uses of Kingston Harbour are being affected by various kinds of pollution. These include substandard bacterial levels along the northern shore as well as in some recreational areas, solid wastes, and oil pollution. However, the most serious pollution from an ecological point of view is the organic pollution resulting from run-off and the discharge of sewage and industrial wastes, and eutrophication resulting from over-fertilization by inorganic nutrients.

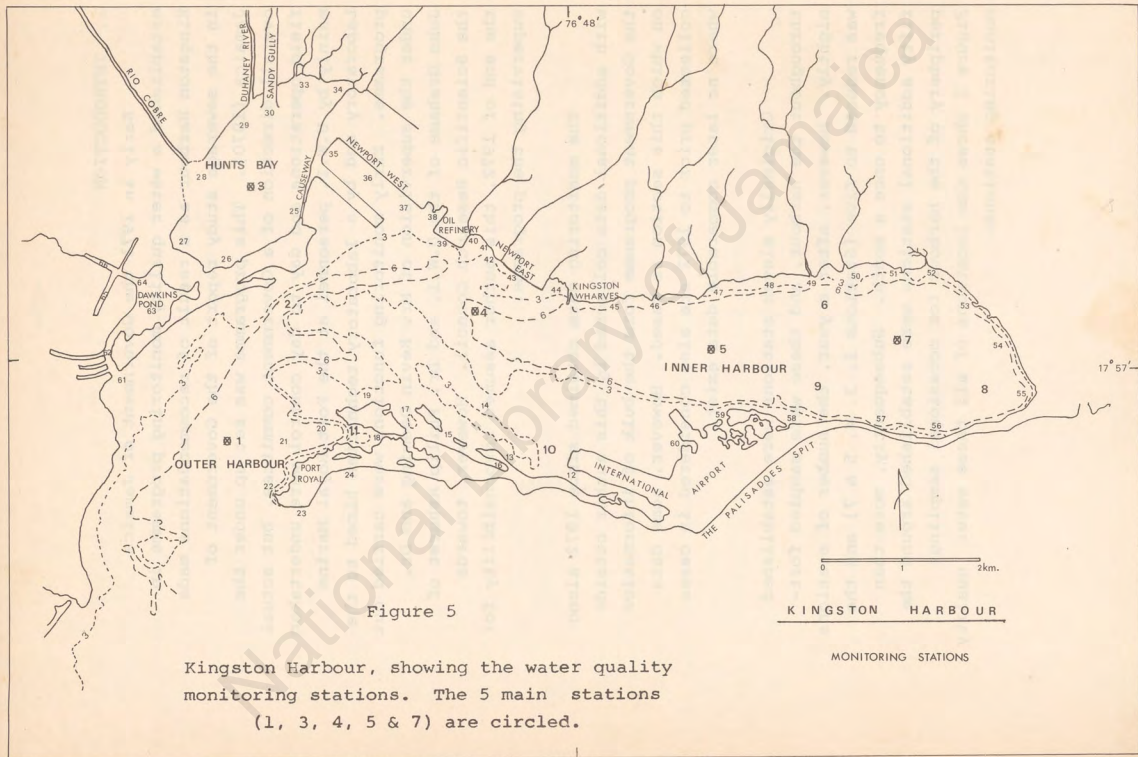
(6) An examination of water quality in the harbour along with a discussion of the factors affecting it are given in Part 2 of this report.

1. INTRODUCTION

Early in 1971 the Government of Jamaica established a water quality monitoring programme in Kingston Harbour as a result of recommendations made in the sewerage study report of the Government of Jamaica (1970). This programme was set up under the overall direction of a Government committee, but actual field operations and day to day control were undertaken mainly by U.W.I. personnel at the Port Royal Marine Laboratory and by a laboratory technician hired to the programme. Early monitoring functions were carried out under the supervision of Mr. Kevin Deeming and Dr. John Grahame of the U.W.I. and Dr. Philip Ashurst of the Scientific Research Council. However, towards the end of 1972, this author assumed responsibility for supervising the programme.

The monitoring data obtained since 1972 along with additional data collected by this author outside the Government programme form the bulk of information on which this section is based. However, some data collected prior to 1972 are also considered in cases where no later comparable data exist.

Originally eleven stations were established throughout the harbour, and these were sampled fortnightly. However, after a year, the number of stations was reduced to five (Stations 1, 3, 4, 5 & 7) and the frequency to once a month. Subsequently, more than fifty additional stations were established around the periphery of the harbour for occasional sampling. Figure 5 shows the locations of all these water quality monitoring stations.



The parameters routinely measured in the monitoring programme were temperature, salinity, transparency, dissolved oxygen, nitrates + nitrites, phosphates and silicates. Additional parameters measured by this author were biochemical oxygen demand (B.O.D.) and suspended solids. Unfortunately, due to equipment and boat failures, there were a number of interruptions in the programme and there is therefore no single year for which complete data for all the parameters exist. Nevertheless, in nearly every case where gaps exist in a year, data for those periods are available in adjacent years.

For purposes of tabulation and illustration of monthly values in this report, the data obtained from May to November, 1973 and December 1974 to April 1975 have been used since the data for most parameters are complete for these periods. However, other data are produced and cited where applicable.

At each station except the shallow ones, monitoring was done at 5 metre depth intervals starting at the surface. Where the depths were insufficient the surface and bottom water (one metre from the mud) were monitored. The actual depths of sampling at the five main stations were as follows:-

Station 1 (Outer Harbour):	0, 5, 10, 13 metres
3 (Hunts Bay):	0, 3 metres
4 (Inner Harbour):	0, 5, 10, 12 metres
5 (Inner Harbour):	0, 5, 10, 15 metres
7 (Inner Harbour):	0, 5, 10, 15, 18 metres

All in situ measurements were made in the mornings between 0800 and 1130 hours.

2. METHODS

Temperature and salinity were measured in situ by means of a Beckman RS5-3 induction salinometer. Periodic checks for accuracy were carried out against a standard thermometer for temperature and silver nitrate titrations for salinity.

Dissolved oxygen was also measured in situ by means of a Delta Scientific Model 85 oxygen meter and probe. Calibration of the instrument using oxygen-saturated distilled water was carried out prior to each day's measurements, and corrections for salinity were made after the measurements using a formula and table supplied by the manufacturers.

Transparency was measured by using a 30 cm diameter oceanographic Secchi Disc.

Water samples for B.O.D., suspended solids and nutrient analyses were obtained with 3-litre van Dorn bottles. The samples were transferred to glass stoppered chemical bottles at sea and on return to the laboratory were either refrigerated or analysed immediately.

B.O.D. was measured using a Hach manometric apparatus (Model 2173) after this equipment had been checked out for accuracy against the standard dilution technique. This method of B.O.D. determination uses the operating principles of the Warburg and Sierp methods in which uptake of oxygen results in a drop in air pressure above the sample with a consequent rise of mercury in the manometer. Since the manometer

sight glass is precalibrated, the B.O.D. as mg/l can be read directly from it. This method has greatly simplified the measurement of B.O.D. and has made it possible to take continuous readings without disturbing the sample. All B.O.D. measurements were made at 20°C over 5 days, unless otherwise stated.

All nutrient determinations were performed with a Technicon Autoanalyzer using procedures specifically developed for maximum accuracy at low concentrations in seawater. After refrigeration, all samples were paper or membrane filtered before analysis.

The determination of nitrate + nitrite utilizes the procedure whereby nitrate is reduced to nitrite by a copper-cadmium reductor column. The nitrite ion then reacts with sulfanilamide under acidic conditions to form a diazo compound. This compound then couples with N-Napthylethylene-diamine to form a reddish-purple Azo dye.

The nitrite method is similar except that the reductor column is dispensed with.

The automated procedure for the determination of soluble phosphate in seawater depends on the reaction whereby phosphate in an acidic molybdate solution forms phosphomolybdic acid which is subsequently reduced with ascorbic acid to form a molybdenum blue complex.

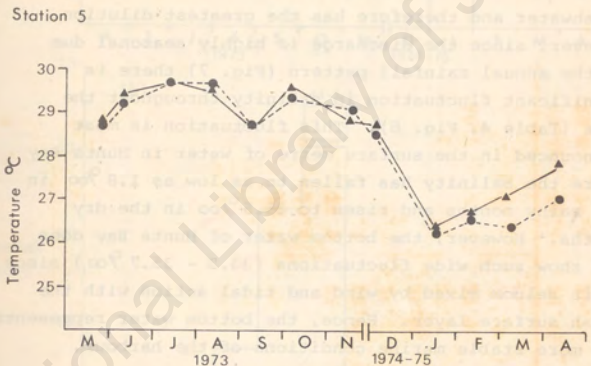
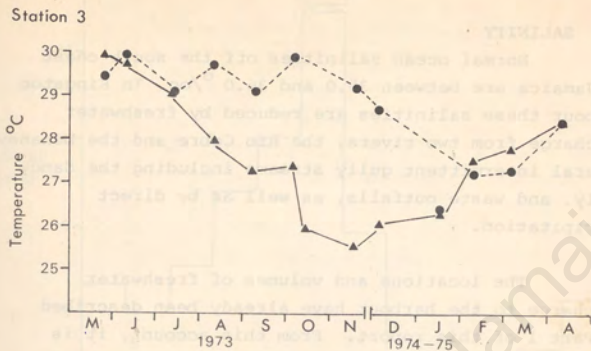
The procedure for the determination of molybdate reactive silicate is based on the reduction of molybdosilicic acid by a-methyl-para aminophenol to form a molybdenum blue complex.

3. TEMPERATURE

A temperature distribution chart for Kingston Harbour was produced for the Government of Jamaica in 1968 based on three months of measurements (November, 1966 - January, 1967) (Government of Jamaica, 1968). This chart showed that except for the region of the harbour near to the Jamaica Public Service generating plant where a heated effluent is discharged, horizontal temperature differences were very small, of the order of 2 - 3°C. Furthermore, the average difference between surface and bottom temperature was only about 0.5°C.

Year round data obtained in this monitoring study substantiate the general conclusion of very small horizontal and vertical temperature differences throughout the harbour. (Table 3, Fig. 6) However, the data indicate that during the rainy months, surface temperatures in Hunts Bay reflect the temperature of run-off stormwater more than that of harbour water. Hence, these temperatures are subject to greater fluctuations than the surface waters in the rest of the harbour.

Station 5 is typical of most of the harbour except Hunts Bay. The annual range of temperature is 3.5°C (26.3 - 29.7°C) with July and August being the warmest months and January to March being the coolest. Horizontal temperature differences across the Inner and Outer Harbour are less than 0.5°C while surface temperatures are on the average less than 0.2°C above bottom temperatures. However, since all the measurements were taken before the daily temperatures reach their maximum it is probable that these differences could be increased by about 1.0 to 1.5°C. However, for all



▲ —▲ Surface
● - - - ● Bottom

Figure 6

Monthly temperature values for station 3
(Hunts Bay) and station 5 (Inner Harbour).

Table 3: Surface and bottom temperature values in °C for the 5 monitoring stations for the periods May - November, 1973, and December, 1974 to April, 1975.

Date	Stn. 1		Stn. 3		Stn. 4		Stn. 5		Stn. 7	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
24.5.73	-	-	29.9	29.4	-	-	28.9	28.7	29.1	29.1
8.6.73	29.2	28.7	29.7	29.9	29.5	29.2	29.4	29.2	29.1	28.9
12.7.73	29.5	29.5	29.1	29.1	29.6	29.6	29.7	29.7	29.7	29.5
10.8.73	29.4	29.3	28.0	29.7	29.4	29.3	29.6	29.7	29.5	29.5
7.9.73	28.4	28.5	27.3	29.1	28.9	28.7	28.7	28.8	28.9	28.8
4.10.73	28.9	29.2	27.4	29.9	29.2	29.4	29.6	29.4	29.7	29.3
16.11.73	28.4	28.9	25.6	29.2	28.3	28.9	28.8	29.1	29.4	29.2
2.12.74	27.7	28.2	26.1	28.7	28.8	28.4	28.7	28.5	28.4	28.6
16.1.75	25.8	26.2	26.3	26.4	26.1	26.2	26.4	26.3	26.6	27.0
8.2.75	-	-	27.5	27.2	-	-	26.8	26.6	-	-
4.3.75	26.3	26.7	27.8	27.3	26.8	26.5	27.1	26.4	27.0	26.0
10.4.75	27.9	27.5	26.4	28.4	28.2	27.8	27.9	27.6	27.7	27.3
AVG.	28.13	28.27	27.75	28.69	28.48	28.40	28.46	28.33	28.64	28.40
MAX.	29.5	29.5	29.9	29.9	29.6	29.6	29.7	29.7	29.7	29.5
MIN.	25.8	26.2	25.6	26.4	26.1	26.2	26.4	26.3	26.6	26.0

4. SALINITY

Normal ocean salinities off the south coast of Jamaica are between 35.0 and 36.0 ‰. In Kingston Harbour these salinities are reduced by freshwater discharge from two rivers, the Rio Cobre and the Duhaney, several intermittent gully streams including the Sandy Gully, and waste outfalls, as well as by direct precipitation.

The locations and volumes of freshwater discharge to the harbour have already been described in Part 1 of this report. From this account, it is clear that Hunts Bay receives the largest amount of freshwater and therefore has the greatest dilution. However, since the discharge is highly seasonal due to the annual rainfall pattern (Fig. 7) there is significant fluctuation in salinity throughout the year (Table 4, Fig. 8). This fluctuation is most pronounced in the surface metre of water in Hunts Bay where the salinity has fallen to as low as 1.8 ‰ in the rainy months and risen to 35.5 ‰ in the dry months. However, the bottom water of Hunts Bay does not show such wide fluctuations (33.3 - 35.7 ‰) since it is seldom mixed by wind and tidal action with the fresh surface layer. Hence, the bottom water represents the more stable marine conditions of the harbour.

The effect of freshwater run-off extends to all stations in the Inner and Outer Harbours although it is greatest at station 4 near Newport East and at station 1 at the mouth of the harbour. At both these stations following rainstorms, the salinity of the top metre of water may be reduced to about 30 ‰ or less

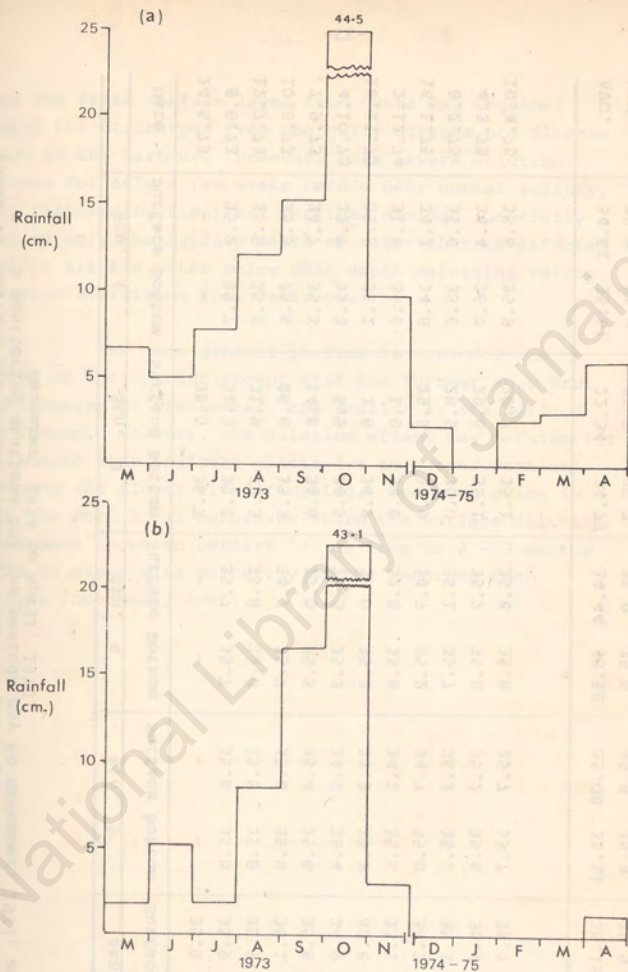


Figure 7

Monthly rainfall at Angels in the Rio Cobre catchment area (a) and at Half-Way-Tree (b) during the monitoring period May to November 1973 and December 1974 to April 1975.

Table 4: Surface and bottom salinity values in parts per thousand for the 5 monitoring stations for the periods May to November, 1973, and December, 1974 to April, 1975.

Date	Stn. 1		Stn. 3		Stn. 4		Stn. 5		Stn. 7	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
24.5.73	-	-	35.5	35.7	-	-	-	-	35.9	35.9
8.6.73	35.2	35.7	31.3	35.2	35.7	35.7	35.8	35.8	35.9	35.9
12.7.73	35.8	35.8	31.9	33.3	35.8	35.8	35.8	35.8	35.9	35.9
10.8.73	35.3	35.6	26.8	35.3	34.7	35.7	35.8	35.9	36.1	36.1
7.9.73	34.7	35.5	14.8	34.8	35.0	35.5	35.4	35.6	35.6	35.8
4.10.73	33.7	35.3	5.9	34.5	31.3	35.3	34.9	35.4	34.9	35.4
16.11.73	33.5	35.2	3.6	34.8	33.0	35.3	33.2	35.2	33.6	35.3
2.12.74	31.5	35.6	1.8	34.6	32.8	35.6	34.2	35.5	33.1	35.6
16.1.75	34.3	34.8	29.5	33.9	34.7	35.2	34.7	35.0	34.7	34.7
8.2.75	35.6	35.6	28.5	35.0	35.1	35.7	35.2	35.2	35.1	35.1
4.3.75	34.4	36.7	29.8	35.1	35.2	35.8	35.2	35.6	35.4	35.4
10.4.75	35.6	35.9	28.7	35.1	35.6	35.8	35.7	35.7	35.7	35.6
AVG.	34.51	35.61	22.34	34.77	34.44	35.58	35.08	35.51	35.15	35.56
MAX.	35.8	35.9	35.5	35.7	35.8	35.8	35.8	35.9	35.9	36.1
MIN.	31.5	34.8	1.8	33.3	31.3	35.2	33.2	35.0	33.1	34.7

as the fresh surface layer from Hunts Bay together with the discharges from the gully streams are flushed out of the harbour. However, this severe dilution lasts for only a few weeks before near normal salinity is restored by tidal and vertical mixing. Generally it is only the surface metre of water that is affected while all the water below this depth maintains fairly stable salinities (See Table 5).

The same general picture is true for the rest of the harbour except that the further away from the source of freshwater, the smaller is the surface dilution. However, the dilution effect may persist for a longer time in these places due to poorer vertical mixing and slower tidal flushing. One such place is in the Port Royal mangroves where the surface dilution has been known to persist for as long as 2 - 3 months and to cause mass mortality of the mangrove root fauna (Goodbody, 1961).

1. Station 1

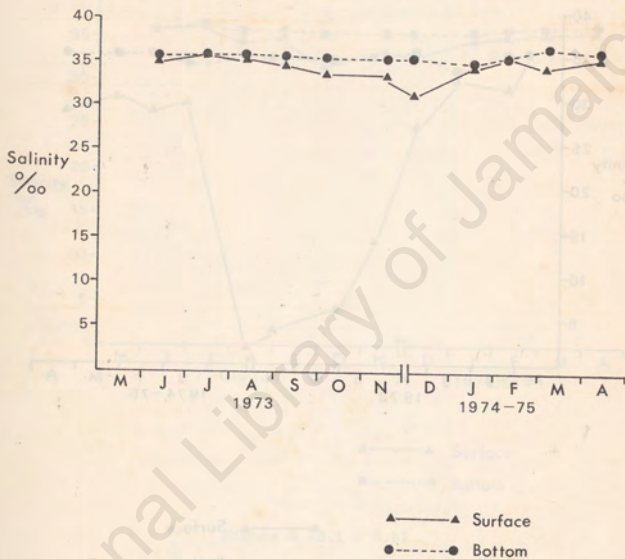


Figure 8 (8.1 - 8.5)

Monthly salinity values for the 5 monitoring stations.

Table 5: Salinity profile measurements for the 5 monitoring stations taken one week after the Gilda flood rains in October 1973.

Depth	S T A T I O N				
	1	3	4	5	7
0 m	28.2 ^o /oo	0.3 ^o /oo	21.6 ^o /oo	18.7 ^o /oo	29.3 ^o /oo
5 m	34.9	33.9 (3 m)	34.3	34.6	34.0
10 m	35.2	-	34.9	34.9	34.8
15 m	35.2 (13m)	-	35.0 (12m)	35.2	35.1
18 m	-	-	-	-	35.2

2. Station 3

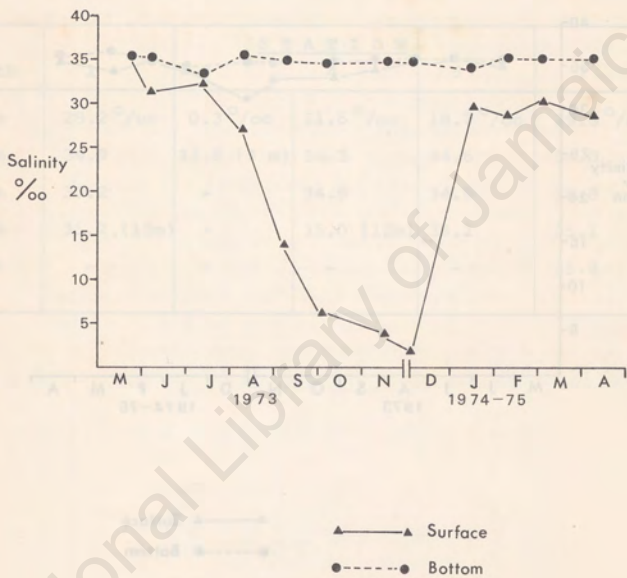


Figure 8 (8.1 - 8.5)

Monthly salinity values for the 5 monitoring stations.

3. Station 4

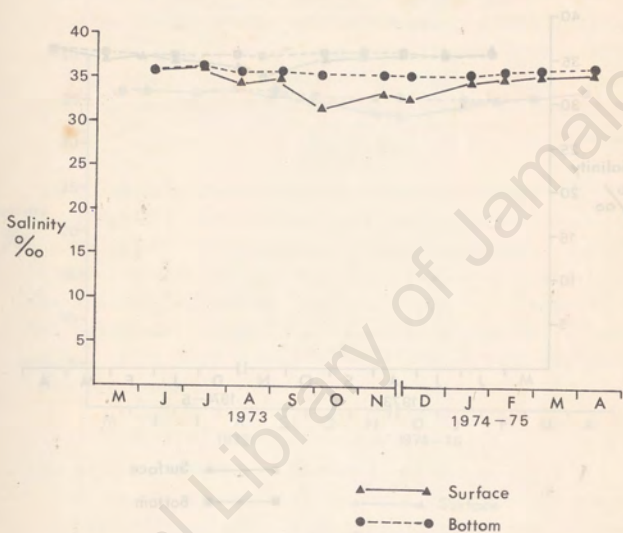


Figure 8 (8.1 - 8.5)

Monthly salinity values for the 5 monitoring stations.

4. Station 5

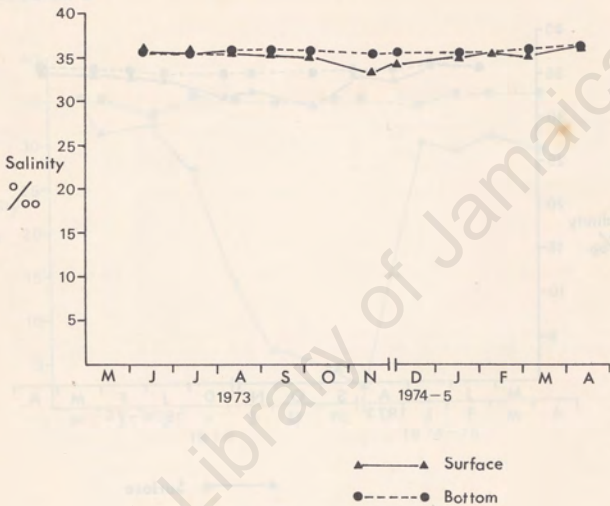


Figure 8 (8.1 - 8.5)

Monthly salinity values for the 5 monitoring stations.

5. Station 7

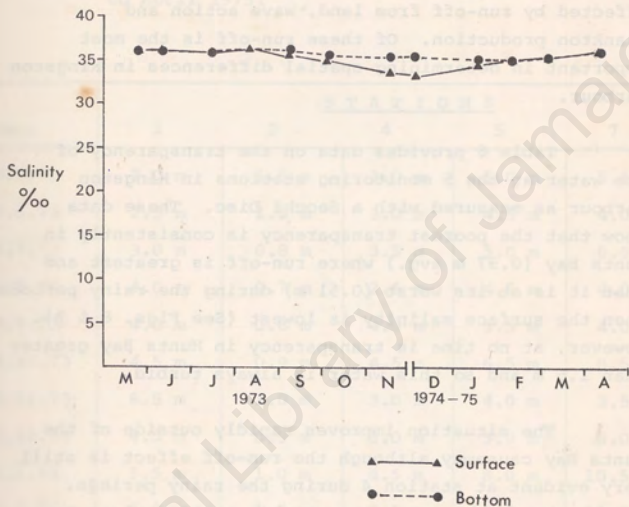


Figure 8 (8.1 - 8.5)

Monthly salinity values for the monitoring stations.

5. TRANSPARENCY

Transparency is a function of the amount of particles in suspension in the water. Hence it may be affected by run-off from land, wave action and plankton production. Of these run-off is the most important in determining spatial differences in Kingston Harbour.

Table 6 provides data on the transparency of the water at the 5 monitoring stations in Kingston Harbour as measured with a Secchi Disc. These data show that the poorest transparency is consistently in Hunts Bay (0.97 m avg.) where run-off is greatest and that it is at its worst (0.51 m) during the rainy periods when the surface salinity is lowest (See Figs. 8 & 9). However, at no time is transparency in Hunts Bay greater than 1.5 m and so this water is always turbid.

The situation improves rapidly outside of the Hunts Bay causeway although the run-off effect is still very evident at station 4 during the rainy periods. Hence, whereas transparency at this station rises to 6.0 m during the dry months, it falls to 2.5 m after rains. However, since this station is located in the vicinity of Newport East where there are waste discharges in the form of sewage, soap and detergent wastes, and slaughterhouse wastes, particulates from these sources also help to reduce the transparency (3.79 m avg.). Another factor affecting transparency in this region is tidal action. During high flood tides, a tongue of clear open-sea water from outside Port Royal may penetrate up into the harbour pass Newport East. At such times, transparency at station 4 improves rapidly

1. Station 1

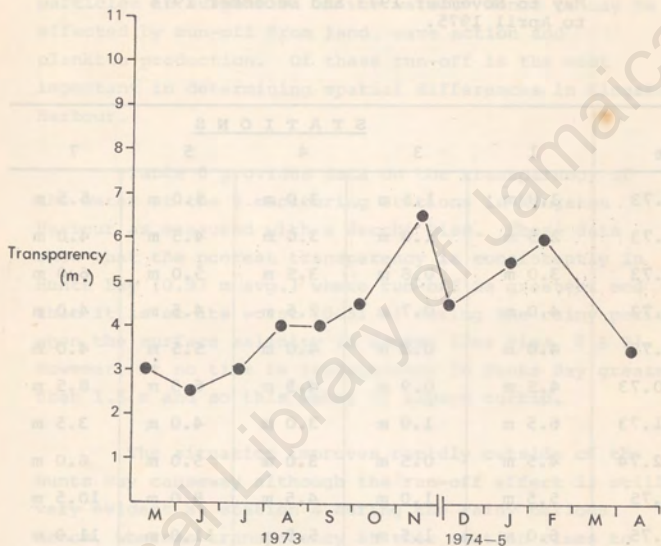


Figure 9 (9.1 - 9.5)

Monthly Secchi Disc transparency values for
the 5 monitoring stations.

Table 6: Secchi Disc Transparency values for the 5 monitoring stations for the periods May to November 1973 and December 1974 to April 1975.

Date	<u>S T A T I O N S</u>				
	1	3	4	5	7
10.5.73	3.0 m	1.5 m	3.0 m	5.0 m	5.5 m
8.6.73	2.5 m	1.0 m	3.0 m	4.5 m	4.0 m
12.7.73	3.0 m	0.8 m	3.5 m	5.0 m	6.0 m
10.8.73	4.0 m	0.7 m	2.5 m	4.5 m	4.0 m
7.9.73	4.0 m	0.8 m	4.0 m	5.5 m	4.0 m
4.10.73	4.5 m	0.9 m	4.5 m	6.5 m	8.5 m
16.11.73	6.5 m	1.0 m	3.0 m	4.0 m	3.5 m
2.12.74	4.5 m	0.5 m	3.0 m	5.0 m	6.0 m
16.1.75	5.5 m	1.0 m	4.5 m	8.0 m	10.5 m
8.7.75	6.0 m	1.5 m	5.5 m	11.0 m	11.0 m
4.3.75	11.0 m	1.0 m	6.0 m	6.0 m	9.0 m
10.4.75	3.5 m	1.0 m	3.0 m	6.5 m	6.5 m
AVG.	4.83 m	0.97 m	3.79 m	5.95 m	6.54 m
MAX.	11.0 m	1.5 m	6.0 m	11.0 m	11.0 m
MIN.	2.5 m	0.5 m	2.5 m	4.0 m	3.5 m

2. Station 3

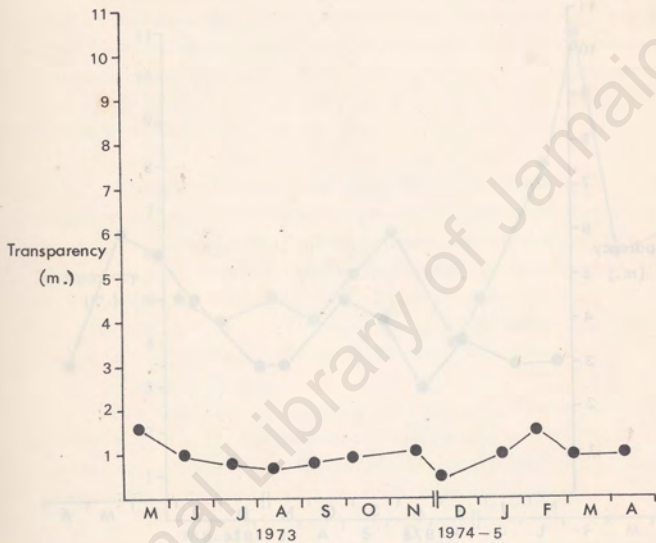


Figure 9 (9.1 - 9.5)

Monthly Secchi Disc transparency values for the 5 monitoring stations.

3. Station 4

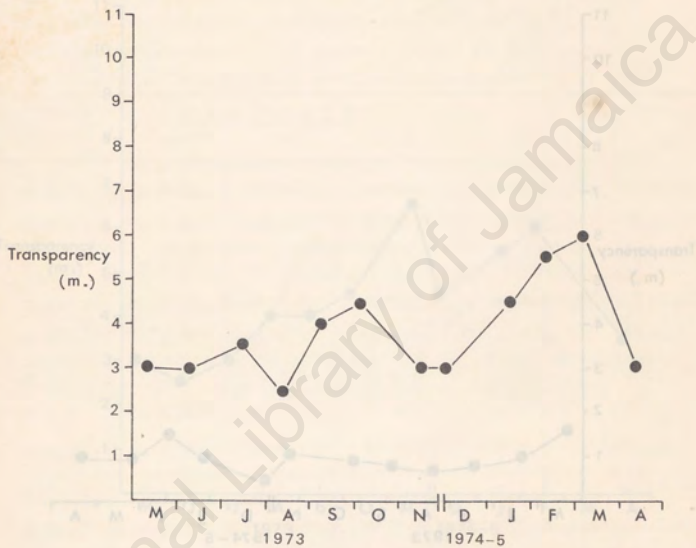


Figure 9 (9.1 - 9.5)

Monthly Secchi Disc transparency values for the 5 monitoring stations.

4. Station 5

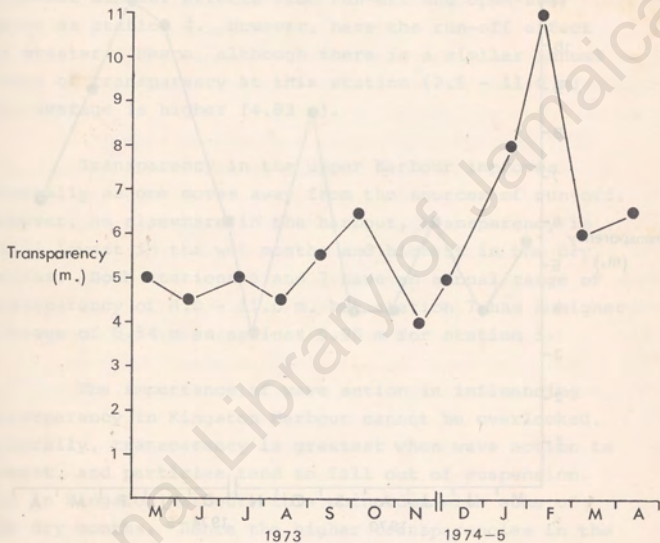


Figure 9 (9.1 - 9.5)

Monthly Secchi Disc transparency values for
the 5 monitoring stations.

5. Station 7

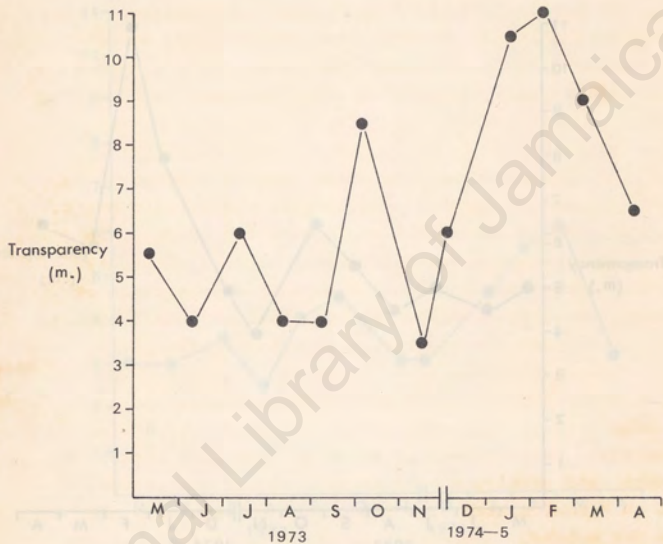


Figure 9 (9.1 - 9.5)

Monthly Secchi Disc transparency values for
the 5 monitoring stations.

(on one occasion reaching 11.0 m), but this is short-lived as on the ebb tide, the more turbid harbour water returns.

Station 1 at the mouth of the harbour shows somewhat similar effects from run-off and open-sea water as station 4. However, here the run-off effect is greater. Hence, although there is a similar annual range of transparency at this station (2.5 - 11.0 m) the average is higher (4.83 m).

Transparency in the upper harbour improves gradually as one moves away from the sources of run-off. However, as elsewhere in the harbour, transparency is still lowest in the wet months and highest in the dry months. Both stations 5 and 7 have an annual range of transparency of 4.0 - 11.0 m, but station 7 has a higher average of 6.54 m as against 5.95 m for station 5.

The importance of wave action in influencing transparency in Kingston Harbour cannot be overlooked. Generally, transparency is greatest when wave action is lowest, and particles tend to fall out of suspension, but in Kingston Harbour, this coincides with some of the dry months. Hence the higher transparencies in the Inner Harbour at such times (January and February), are due not to any single factor but to a combination of low run-off and low wave action. Nevertheless, it is doubtful whether wave action can account for any of the spatial differences at the 5 stations throughout the harbour since all the stations are subject to more or less similar wave action.

Yet another factor influencing transparency is plankton production and much of the generally low transparency in Kingston Harbour is undoubtedly due to the huge populations of planktonic organisms which thrive in the water. However, in the absence of any experimental evidence, it is impossible to say quantitatively how great the effect is. Nevertheless, it has been noted in Kingston Harbour that during periods of plankton blooms and red tides, transparencies may be reduced by as much as 50%.

Most of the above discussion pertains to transparency at the 5 monitoring stations. However, there are a number of places around the periphery of the harbour where transparency is affected by local factors such as waste discharges, ship traffic and dredging operations. Most of these are in the Newport East - Newport West areas where industrial activity is concentrated. In many of these places transparency may fall below 2 metres.

6. DISSOLVED OXYGEN

Dissolved oxygen concentrations are quite varied throughout Kingston Harbour. Thus conditions may range from severe oxygen depletion to either saturation or supersaturation depending on the location, season, and time of day. Data obtained at the 5 monitoring stations and produced in Table 7, show the range of D.O. concentrations occurring within the harbour and form the basis for a discussion of the factors affecting them.

Average monthly values for each station obtained by incorporating all the readings from 5 metre depth intervals suggest that on the whole D.O. levels are high (Table 7). For example, the lowest annual average obtained was 4.10 mg/l (66.1 % saturation) at station 7 while the highest annual average was 5.69 mg/l (91.7 % saturation) at Hunts Bay. Stations 4, 5 and 7 appear to be grouped around similar values, but with a gradual decrease going up the harbour, while stations 1 and 3 are almost identical. Highest values occur in March - May, while the lowest values are in September - November. However, these average values are very inadequate for they do not reveal the differences that exist between surface and bottom. Hence, in order to appreciate the true conditions at each station, surface and bottom values must be considered separately.

Taking surface values first (Fig. 10.1 - 10.5), we see that at all stations throughout the year D.O. levels are very high and may even reach supersaturation. Only at one station on one occasion was a surface oxygen concentration of less than 65% saturation (4 mg/l) recorded (Fig. 10.5). Hence,

as far as the surface waters are concerned, there good oxygenation at all stations throughout the year

The same is not true for bottom waters. In the first place, D.O. concentrations are nearly always lower at the bottom than at the surface, and on a number of occasions, especially at stations 5 and 7, they have reached zero. Secondly, there are pronounced seasonal fluctuations in D.O. concentration at the bottom. And thirdly, whereas surface values are more or less similar at all stations (except Hunts Bay) bottom values are strikingly different and follow a definite pattern. We shall examine each of these aspects separately.

At station 1 near the mouth of the harbour, D.O. levels at the bottom are on an average 0.92 mg/l less than at the surface while at station 3 in Hunts Bay, the average difference between the surface and bottom is 4.02 mg/l. Stations 4, 5 and 7 in the Inner Harbour show average differences of 1.53, 2.56 and 2.92 mg/l respectively. However, except for station 1 where the difference at any one time is never greater than 2.5 mg/l, all the other stations may have differences between surface and bottom of more than 6 mg/l. Hence, at all stations except 1, it is possible on occasions to have anoxia at the bottom while having oxygen saturation or even supersaturation at the surface (See Figs. 10.5 and 12). For this reason the surface and bottom cannot be considered together when evaluating water quality in terms of dissolved oxygen concentrations.

3. Station 4

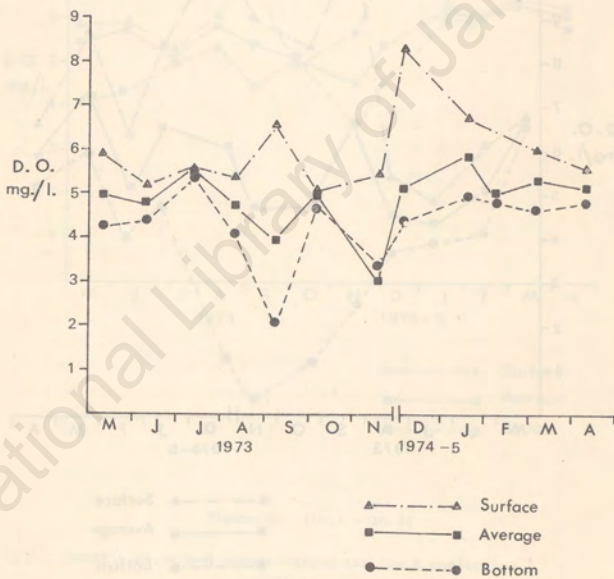
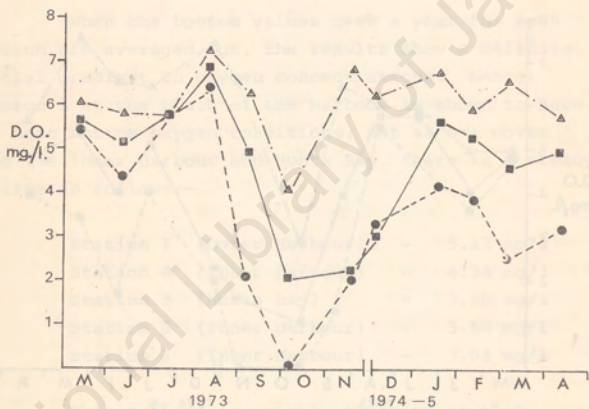


Table 7: Surface, bottom and average D.O. concentrations in mg/l for the 5 monitoring stations for the periods May - November, 1973, and December 1974 to April 1975

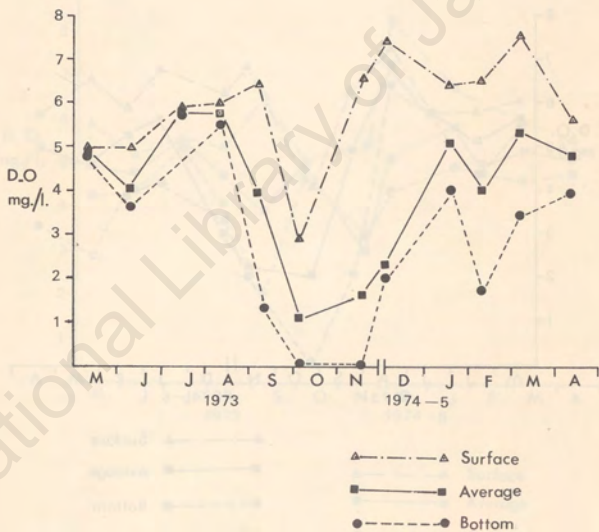
Date	Stn. 1			Stn. 3			Stn. 4			Stn. 5			Stn. 7		
	Surf.	Bot.	Avg.	Surf.	Bot.	Avg.	Surf.	Bot.	Avg.	Surf.	Bot.	Avg.	Surf.	Bot.	Avg.
10.5.73	5.86	4.03	5.46	6.76	6.60	6.68	5.86	4.28	4.99	6.02	5.57	5.64	4.99	4.91	4.86
8.6.73	5.86	5.31	5.70	6.12	4.19	5.15	5.15	4.36	4.79	5.78	4.36	5.15	5.00	3.64	4.08
12.7.73	5.28	4.97	5.14	4.86	3.98	4.42	5.52	5.36	5.46	5.75	5.75	5.80	5.90	5.75	5.87
10.8.73	6.02	5.31	5.82	5.39	3.72	4.55	5.33	4.12	4.73	7.23	6.45	6.85	5.98	5.52	5.81
7.9.73	6.91	4.44	5.47	10.83	2.54	6.68	6.52	2.06	3.95	6.26	2.06	4.99	6.42	1.35	4.05
4.10.73	4.89	5.09	5.12	8.40	1.27	4.83	5.10	4.69	4.99	4.05	0.08	2.06	2.86	0.00	1.16
16.11.73	5.69	3.66	4.62	9.04	0.48	4.76	5.41	3.34	3.06	6.79	2.07	2.27	6.59	0.00	1.62
2.12.74	7.15	4.52	5.47	10.89	1.35	6.12	8.29	4.43	5.16	6.24	3.23	3.07	7.43	2.05	2.30
16.1.75	6.54	6.09	6.18	8.42	4.79	6.60	6.73	4.99	5.86	6.73	4.12	5.68	6.48	4.01	5.18
8.2.75	5.86	5.94	6.08	6.41	4.08	5.24	5.09	4.93	5.03	5.88	3.89	5.24	6.52	1.67	4.02
4.3.75	6.32	6.43	6.37	8.72	6.00	7.36	6.00	4.70	5.39	6.56	2.53	4.68	7.59	3.48	5.40
10.4.75	6.26	5.78	6.06	6.62	5.26	5.94	5.55	4.83	5.15	5.71	3.25	4.99	5.63	3.96	4.86
AVG.	6.05	5.13	5.62	7.70	3.68	5.69	5.87	4.34	4.88	6.16	3.60	4.70	5.94	3.02	4.10
% SATN.	97.58	82.74	90.64	100.00	59.35	91.77	94.67	70.00	78.70	99.35	58.06	75.80	95.80	48.70	66.12
MAX.	6.91	6.43	6.08	10.89	6.60	6.68	8.29	5.36	5.46	7.23	6.45	6.85	7.57	5.75	5.87
MIN.	4.89	3.66	4.42	4.86	0.48	4.55	5.09	2.06	3.06	4.05	0.08	2.06	2.86	0.00	1.16

4. Station 5



- ▲ - - - - - Surface
- - - - - - Average
- - - - - - Bottom

5. Station 7



All bottom values for oxygen at the monitoring stations show a seasonal fluctuation, but this is most pronounced in Hunts Bay and the Inner Harbour (Fig. 10.2 - 10.5). Generally, the highest oxygen concentrations at the bottom occur during the dry, windy months of March, April and May while the lowest concentrations are in the rainy months of September, October and November. The range between the bottom maximum and minimum for each station is 2.77 mg/l at station 1, 6.12 mg/l at station 3, 3.30 mg/l at station 4, 6.37 mg/l at station 5 and 5.75 mg/l at station 7.

When the bottom values over a year for each station are averaged out, the results show a definite spatial gradient in oxygen concentrations. Hence, station 1 at the mouth of the harbour is shown to have the best bottom oxygen conditions, but as one moves into the Inner Harbour and Hunts Bay, there is a steady decline as follows:-

Station 1 (Outer Harbour)	-	5.13 mg/l
Station 4 (Inner Harbour)	-	4.34 mg/l
Station 3 (Hunts Bay)	-	3.68 mg/l
Station 5 (Inner Harbour)	-	3.60 mg/l
Station 7 (Inner Harbour)	-	3.02 mg/l

This pattern is exactly the same as that described by Wade et al (1972) using 1971 values. However, in the present case, the D.O. concentrations are considerably lower in the Outer Harbour, Hunts Bay and the Inner Harbour (Station 4) as shown by the following percent saturation levels:

	<u>1971</u>	<u>1973-75</u>
Station 1 (Outer Harbour)	90.3%	82.7%
Station 3 (Hunts Bay)	75.8%	59.3%
Station 4 (Inner Harbour)	72.6%	70.0%
Station 5 (Inner Harbour)	56.5%	58.1%
Station 7 (Inner Harbour)	48.4%	48.7%

In order to understand more clearly the horizontal and seasonal variations in oxygen levels throughout the harbour, it is necessary to examine the distribution of oxygen in the water column and to consider some of the factors affecting it.

The ideal oxygen profile is one in which there is saturation at all levels. This occurs fairly frequently at station 1, but only rarely at the other stations and only on those occasions when wave action is strong enough as to cause complete vertical mixing. Because of the shallow depth at Hunts Bay, the occurrence of complete mixing tends to be more frequent than at the other stations. However, this has largely been offset in recent years by the construction of the solid fill causeway which has served to reduce wave fetch and thus limit wave action. At the deeper parts of the Inner Harbour (Stations 5 and 7) complete vertical mixing is only accomplished when winds in excess of 15 knots blow throughout the day and during storms and hurricanes. Since the former condition is most frequent during the windy months of March to August, it is at these times that saturation to all depths most commonly occurs. Nevertheless the frequency is low, and in the four years that this parameter has been monitored, complete saturation has been recorded on

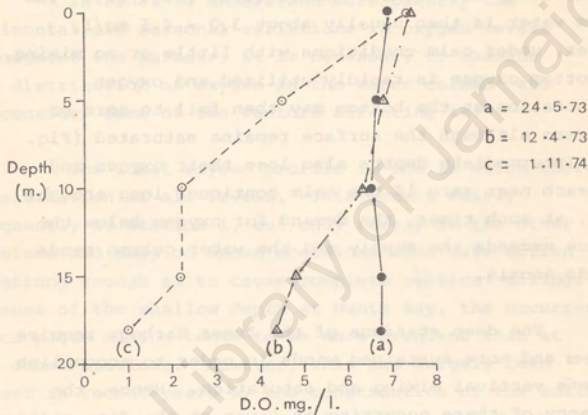


Figure 11

Dissolved oxygen profiles at station 7 in
 the Inner Harbour under different wind
 conditions: (a) sustained strong winds;
 (b) moderate winds; (c) no winds.

only a few occasions at stations 5 and 7. The profile obtained on one such occasion at station 7 is shown in Figure 11.

More commonly when there are gentle, moderate or unsustained strong winds, the surface water may be saturated but there is a sharp decline in oxygen concentration below the 10 metre level (Fig. 11). The bottom water is then usually about 3.0 - 4.5 mg/l. However, under calm conditions with little or no mixing, the bottom oxygen is rapidly utilised and oxygen concentration at the bottom may then fall to zero or near zero although the surface remains saturated (Fig. 11). Intermediate depths also lose their oxygen and may reach near zero if the calm continues long enough. Hence, at such times, the demand for oxygen below the surface exceeds the supply and the water column tends towards anoxia.

The deep stations of the Inner Harbour require stronger and more sustained winds in order to accomplish complete vertical mixing and saturation. Hence, the frequency of these occurring is lower at the deep stations, and their bottom waters thus go for longer periods without replenishment. This is one of the reasons why D.O. concentration at the bottom falls off as one moves from station 4 into the deeper waters of stations 5 and 7. It is also one of the reasons why the highest oxygen concentrations occur at the bottom during the windy months.

In addition to wind, a second factor influencing oxygen concentration is plankton. Phytoplankton give off oxygen in the process of photosynthesis and,

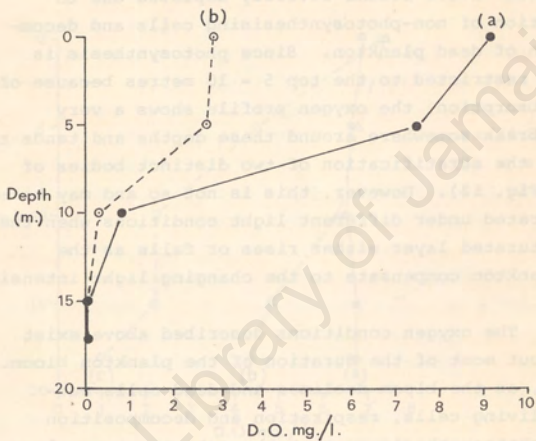


Figure 12

Dissolved oxygen profiles at station 7
in the Inner Harbour during a plankton
bloom: (a) early bloom; (b) late bloom.

together with zooplankton, take up oxygen in respiration. The effect on oxygen concentrations in Kingston Harbour is most pronounced when there are plankton blooms or red tides. At these times, the surface waters become supersaturated with oxygen during daylight hours because of very high photosynthetic activity, while the bottom waters become severely depleted due to respiration of non-photosynthesising cells and decomposition of dead plankton. Since photosynthesis is largely restricted to the top 5 - 10 metres because of light absorption, the oxygen profile shows a very sudden break somewhere around these depths and tends to suggest the stratification of two distinct bodies of water (Fig. 12). However, this is not so and may be demonstrated under different light conditions when the supersaturated layer either rises or falls as the phytoplankton compensate to the changing light intensity.

The oxygen conditions described above exist throughout most of the duration of the plankton bloom. However, as the bloom declines and dead cells outnumber living cells, respiration and decomposition exceed photosynthesis so that the entire water column becomes oxygen depleted (Fig. 12). This continues for a time until decomposition of the dead plankton declines and normal photosynthetic activity is restored in the surface layers. Surface oxygen then increases again and eventually, the entire water column recovers its normal oxygen levels.

The overall effect of plankton blooms on oxygen concentrations in Kingston Harbour depends on their location, frequency, duration and intensity. In

recent years, these blooms have been occurring with increasing frequency and over wider areas of the harbour. A few generalisations may be made about them here although the report of E.S. Grahame should be consulted for further detail.

Blooms occur most frequently in Hunts Bay and the Inner Harbour during the rainy months of September, October and November, and sometimes June. Steven (1966) studied one such bloom which occurred in October, 1962, and found that it was associated with increased nutrients and lowered salinity. However, he was unable to determine a direct cause and effect. Nevertheless, almost all the blooms which have been monitored in Kingston Harbour since then have occurred under similar conditions thus suggesting that run-off is an important factor.

Several species of dinoflagellates (Exuviella sp., Gymnodinium splendens, Peridinium sp., Gonyaulax sp., Ceratium furca), diatoms and ciliates are responsible for plankton blooms in Kingston Harbour, and the nature of the blooms usually depends on which species are involved. Most commonly, however, a single bloom lasts from one to two weeks and may cover an area of one half to several square miles. Frequently, the entire Hunts Bay experiences a single bloom at a time but only occasionally does a bloom extend over more than two stations within the Inner Harbour. Generally stations 5 and 7 share a single bloom while station 4 tends to be separate and to have blooms which are more associated with Hunts Bay. Station 1 in the Outer Harbour also has separate blooms.

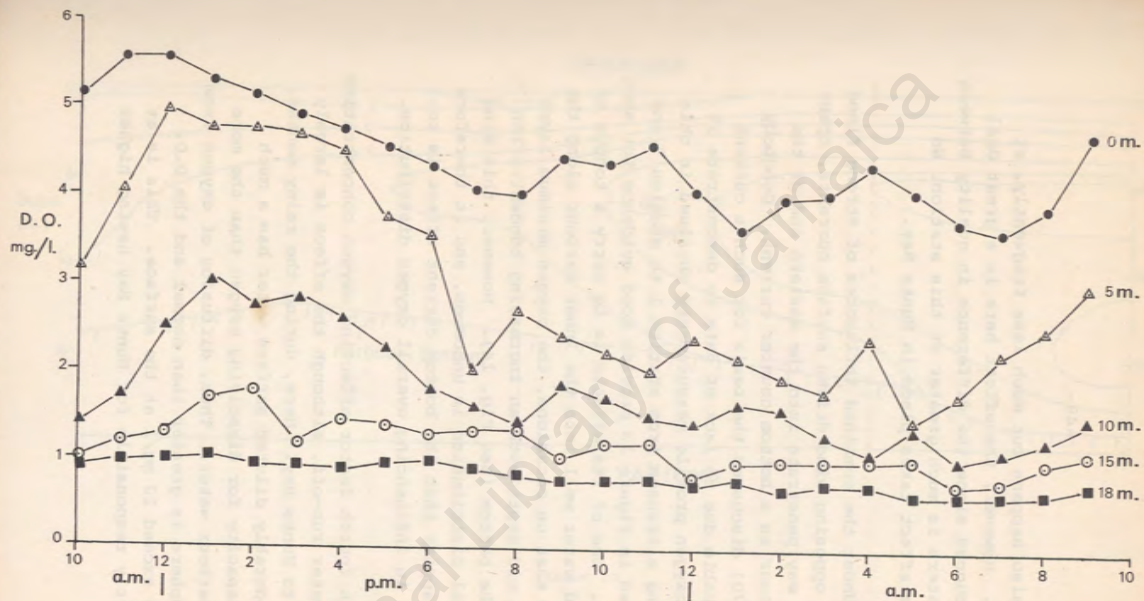


Figure 13

The diurnal variation in dissolved oxygen concentrations at various depths at station

7 in the Inner Harbour.

All the Inner Harbour stations and Hunts Bay experience several plankton blooms in a year and, in 1973, more than six blooms were recorded at each. However, the occurrence of blooms in the Outer Harbour is less frequent and only two were recorded in 1973.

Although the most pronounced effects of wind and plankton are seasonal, diurnal effects are also important and follow a regular pattern. Thus during the afternoons when the sea breezes are strongest and oxygen production by photosynthesis is greatest, oxygen levels throughout the water column are at their maximum. However, as night falls, the winds die down and photosynthesis ceases, with the result that oxygen concentrations decline. This continues steadily throughout the night until at first light next day, photosynthesis recommences and the D.O. concentration begins to rise again. This is aided by the freshening sea breeze throughout the morning, so that by early afternoon, the maximum D.O. level is once more reached (Fig. 13). The largest diurnal variations occur at mid depth and at those times of the year when wind fluctuation throughout the day is greatest and there are plankton blooms. At such times, the variation may exceed 3.5 mg/l as shown in Figure 13.

A third factor affecting oxygen concentration in Kingston Harbour is water circulation. At station 1 near the mouth of the harbour, there is sometimes a complete exchange of harbour and open-sea waters at spring tide. At such times, oxygen concentrations usually rise as the harbour water is replaced by the cleaner and more oxygenated open-sea water.

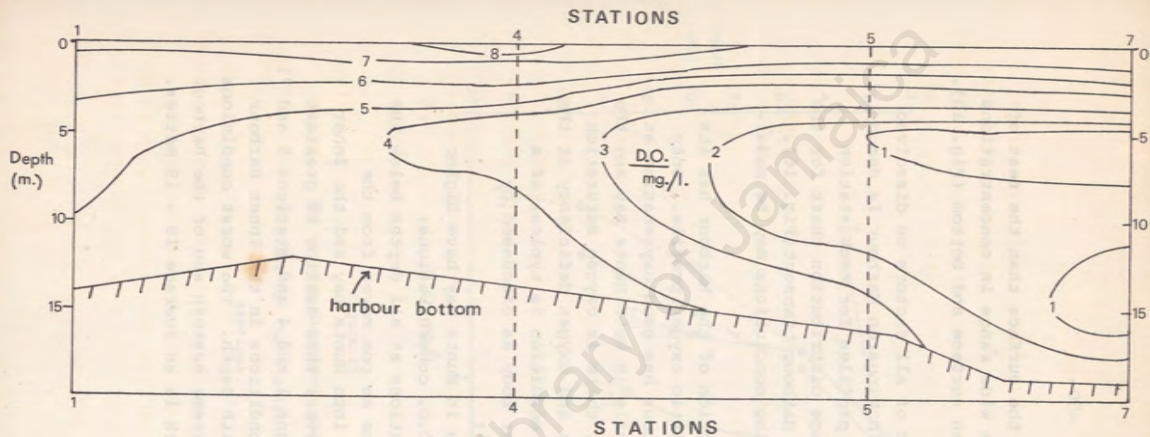


Figure 14

The distribution of dissolved oxygen in mg/l along a transect from station 1 in the Outer Harbour to station 7 in the Inner Harbour, showing the effect of the bottom counter current.

The same also happens but much less frequently, at station 4. However, the effect here is a great deal more pronounced since the difference in quality between the two waters is much greater at this station. No comparable effect takes place in Hunts Bay.

Under the combined influences of strong flood tides and opposing wind driven surface currents, open-sea water may penetrate into the eastern end of the Inner Harbour as a bottom counter current. Goodbody (1968, 1970) discussed the basis for such a current but was unable due to lack of data to demonstrate it. However, oxygen profile measurements obtained in this study along a transect from station 1 to station 7 and illustrated in Figure 13 provide good evidence for such a current. One of its effects is to carry a tongue of oxygenated water well into the Inner Harbour along the bottom so that on occasions, the oxygen minimum layer may be at mid depth with an increasing concentration towards the bottom (See Fig. 14). However, this kind of vertical distribution is uncommon, and it therefore does not appear that the bottom current effect is too important in influencing overall oxygen distribution.

A fourth factor affecting oxygen concentration is freshwater run-off, although the effect is largely confined to Hunts Bay. Here, during the rainy months, the considerably diluted surface water has a much greater capacity for dissolving oxygen than the more saline harbour water. Thus, diffusion of oxygen from the atmosphere is greater than normal and the D.O. level may exceed 10 mg/l at the surface. This is at least partly responsible for Hunts Bay having higher

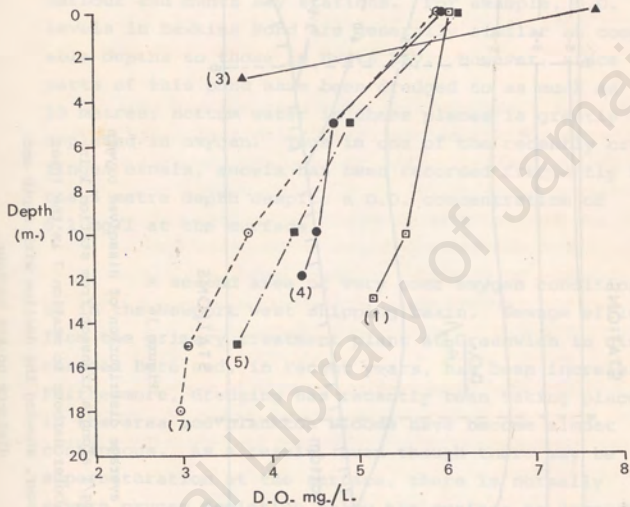


Figure 15

The average dissolved oxygen profiles for the 5 monitoring stations.

D.O. concentrations at the surface than the rest of the harbour and for the wide range in concentrations which exist here between surface and bottom (Fig. 10).

The net result of all factors on dissolved oxygen concentrations in Kingston Harbour is demonstrated by the average profiles for each station (Fig. 15) and the average distribution chart for the Outer Harbour to Inner Harbour transect (Fig. 16). From these, the following conclusions may be made:-

- (i) Each major section of the harbour has its own characteristic oxygen profile. Only the Outer Harbour has good oxygenation at all depths, while in both Hunts Bay and the Inner Harbour, there is oxygen saturation at the surface and oxygen deficiency at the bottom. This condition is typical of a eutrophic water body as discussed by Grahame (1974);
- (ii) Surface waters in Hunts Bay have higher than average D.O. concentrations;
- (iii) D.O. concentrations at all depths below the surface decline as one moves from the Outer Harbour into Hunts Bay and the Inner Harbour. However, this decline is greatest between stations 1 and 4 and stations 5 and 7;
- (iv) Bottom D.O. conditions in the Inner Harbour deteriorate with depth. The worst conditions are in the extreme eastern end of the harbour where the depth is an average 18 - 19 metres.

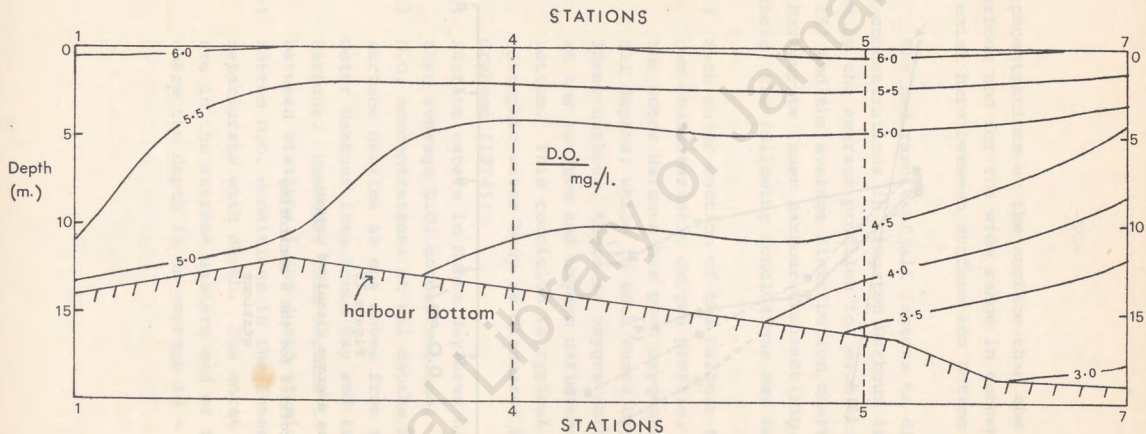


Figure 16

The average distribution of dissolved oxygen in mg/l along a transect from station 1 in the Outer Harbour to station 7 in the Inner Harbour, showing the decline with depth and distance up the harbour.

Data obtained by occasional sampling in peripheral parts of the harbour indicate that, in a number of places, oxygen conditions are worse than at the Inner Harbour and Hunts Bay stations. For example, D.O. levels in Dawkins Pond are generally similar at comparable depths to those in Hunts Bay. However, since some parts of this pond have been dredged to as much as 10 metres, bottom water in these places is greatly depleted in oxygen. Thus in one of the recently created finger canals, anoxia has been recorded frequently below the 5 metre depth despite a D.O. concentration of 6.1 mg/l at the surface.

A second area of very poor oxygen conditions is in the Newport West shipping basin. Sewage effluent from the primary treatment plant at Greenwich is discharged here and, in recent years, has been increasing. Furthermore, dredging has recently been taking place in the area and plankton blooms have become almost continuous. As a result, even though there may be supersaturation at the surface, there is normally severe oxygen depletion below the surface as demonstrated by the following values:

Surface	-	8.00 mg/l
5 m	-	1.67 mg/l
10 m	-	0.00 mg/l

Smaller areas of poor oxygen conditions exist near the mouths of gully streams and waste outfalls. One such place in particular is the small bay between Newport East and the old Kingston Wharves into which all the liquid wastes from the city abattoir are

discharged. D.O. level here is only slightly more than 50% saturation at the surface while the bottom is usually anoxic as the figures indicate.

Surface	-	3.18 mg/l
5 m	-	0.00 mg/l

The Port Royal mangrove area has variable and interesting oxygen conditions. In most parts, surface oxygenation is high and exceeds 5.0 mg/l. However, depending on the tidal circulation, bottom levels may fluctuate from saturation to near anoxia between the flood and ebb tides in response to replenishment by incoming currents and rapid uptake by benthic deposits. However, where circulation is poor, oxygen levels may be permanently depressed.

The best oxygen conditions in Kingston Harbour occur in shallow water above turtle grass beds. In these places supersaturation from surface to bottom is not uncommon.

7. BIOCHEMICAL OXYGEN DEMAND

The Biochemical Oxygen Demand (B.O.D.) of surface and bottom water at the 5 monitoring stations in Kingston Harbour was measured routinely from February to October, 1973, and occasionally at other times. The data for the 9 months are given in Table 8 and are illustrated in Figure 17.

The data show that the highest B.O.D.'s occurred in Hunts Bay where the combined monthly average for surface and bottom was 7.25 mg/l over the 9 month period. The next highest was at station 4 in the Inner Harbour (5.05 mg/l) followed by stations 5 (4.58 mg/l) and 7 (4.05 mg/l) in the Inner Harbour, and then station 1 (3.51 mg/l) in the Outer Harbour. This order was remarkably consistent throughout the entire sampling period and it indicates strongly that the major sources of B.O.D. input into the harbour are in Hunts Bay and in the vicinity of station 4. This is not surprising since these two areas are the major receivers of run-off and waste effluents in Kingston Harbour.

Typically at all stations, the surface water had a higher B.O.D. than the bottom water (Figs. 17 & 18), but this was least pronounced at stations 5 and 7 in the Inner Harbour. However, there were a number of occasions at nearly all stations (station 1 being the exception), when the bottom water had a slightly higher B.O.D. The difference between surface and bottom B.O.D. at all stations was greatest following rains and this suggests that the high surface B.O.D. at these times was due to the freshwater run-off. However, this is only partly true as will be shown below.

1. Station 1

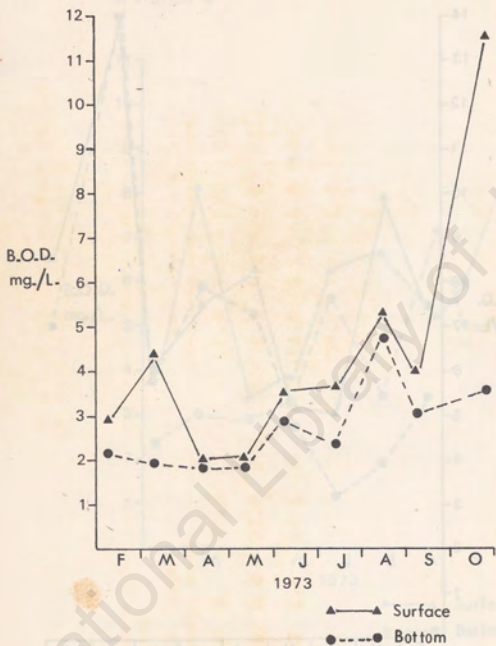


Figure 17 (17.1 - 17.5)

The monthly surface and bottom B.O.D. values for the 5 monitoring stations.

Table 8: Surface, bottom and average B.O.D. values in mg/l for the 5 monitoring stations for the period February - October, 1973.

Date	Stn. 1			Stn. 3			Stn. 4			Stn. 5			Stn. 7		
	Surf.	Bot.	Avg.	Surf.	Bot.	Avg.	Surf.	Bot.	Avg.	Surf.	Bot.	Avg.	Surf.	Bot.	Avg.
8.2.73	2.9	2.2	2.55	7.3	5.4	6.35	4.0	2.3	2.85	5.2	4.8	5.00	2.7	5.0	3.85
8.3.73	4.4	2.0	3.20	9.9	3.9	6.90	8.1	3.0	5.55	6.6	3.8	5.20	5.1	4.0	4.55
12.4.73	2.0	1.0	1.90	5.0	3.2	4.10	3.4	2.9	3.15	3.1	2.8	2.95	3.2	3.3	3.25
10.5.73	2.1	1.8	1.95	5.1	4.7	4.90	3.8	3.3	3.55	4.2	4.0	4.10	2.2	2.0	2.10
7.6.73	3.5	2.8	3.15	8.3	7.3	7.80	6.2	5.6	5.90	4.7	4.2	4.45	5.1	4.9	5.00
12.7.73	3.6	2.3	2.95	9.5	7.9	7.70	6.6	3.4	5.00	4.0	4.7	4.35	5.8	4.0	4.90
16.8.73	5.3	4.7	5.00	6.1	5.8	5.95	5.2	7.1	6.15	3.4	5.0	4.20	4.5	1.8	3.15
7.9.73	4.0	3.0	3.50	13.8	14.0	13.90	6.0	5.0	5.50	3.0	4.2	3.60	4.6	2.5	3.55
25.10.73	11.5	3.5	7.50	8.5	7.0	7.75	10.2	5.0	7.60	8.5	6.30	7.40	8.2	4.0	6.10
AVG.	4.36	2.67	3.51	7.94	6.57	7.25	5.94	4.17	5.05	4.74	4.42	4.58	4.60	3.50	4.05
MAX.	11.5	4.7		13.8	14.0		10.2	7.1		8.5	6.3		8.2	5.0	
MIN.	2.0	1.8		5.0	3.2		3.4	2.3		3.1	2.8		2.2	1.8	

2. Station 3

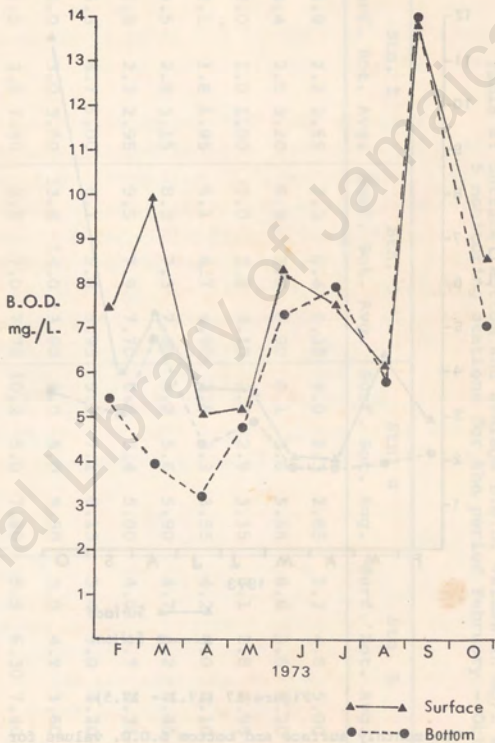


Figure 17 (17.1 - 17.5)

The monthly surface and bottom B.O.D. values for the 5 monitoring stations.

3. Station 4

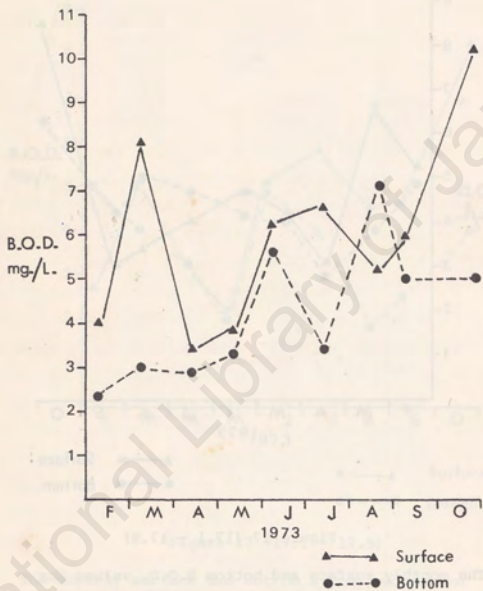


Figure 17 (17.1 - 17.5)

The monthly surface and bottom B.O.D. values for the 5 monitoring stations.

4. Station 5

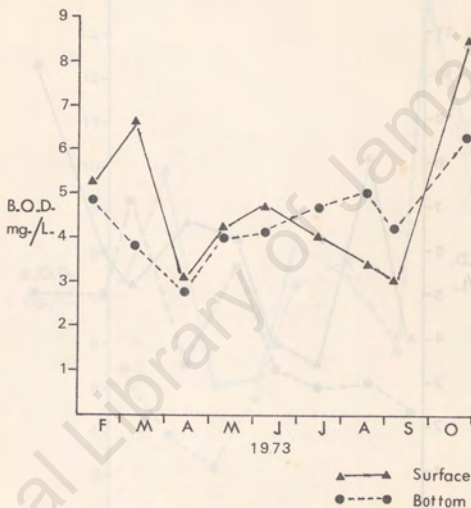


Figure 17 (17.1 - 17.5)

The monthly surface and bottom B.O.D. values for the 5 monitoring stations.

5. Station 7

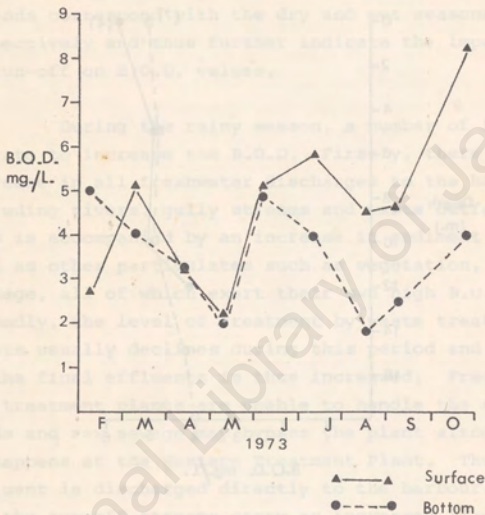


Figure 17 (17.1 - 17.5)

The monthly surface and bottom B.O.D. values for the 5 monitoring stations.

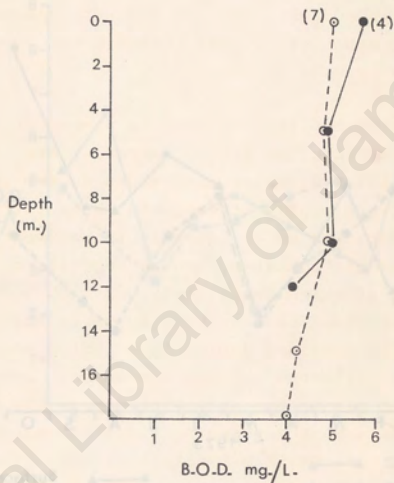


Figure 18

Typical B.O.D. profiles for stations 4 and 7, showing the decrease with depth.

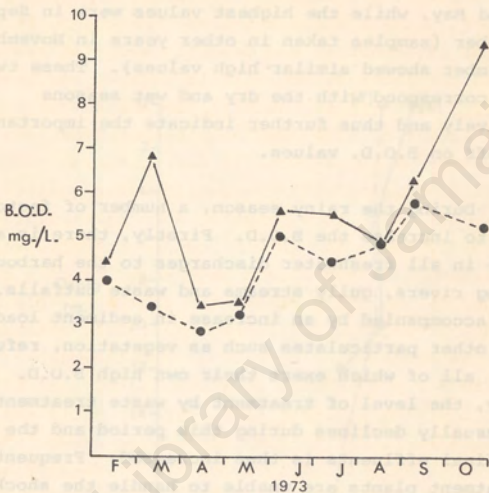


Figure 19

The average monthly B.O.D. values for all stations combined to show the seasonal pattern.

The B.O.D. at all stations tended to show a definite seasonal pattern, both at the surface and bottom (Fig. 19) The lowest values were in March, April and May, while the highest values were in September and October (samples taken in other years in November and December showed similar high values). These two periods correspond with the dry and wet seasons respectively and thus further indicate the importance of run-off on B.O.D. values.

During the rainy season, a number of factors operate to increase the B.O.D. Firstly, there is an increase in all freshwater discharges to the harbour, including rivers, gully streams and waste outfalls. This is accompanied by an increase in sediment load as well as other particulates such as vegetation, refuse and garbage, all of which exert their own high B.O.D. Secondly, the level of treatment by waste treatment plants usually declines during this period and the B.O.D. of the final effluents is thus increased. Frequently, the treatment plants are unable to handle the shock loads and raw sewage may bypass the plant altogether as happens at the Western Treatment Plant. Thus raw effluent is discharged directly to the harbour. Thirdly, all the run-off streams carry an increased load of soluble organics collected from agricultural land, roads, factories etc. And fourthly, there is an increased input of inorganic nutrients (nitrates, phosphates, silicates) which encourage plankton blooms throughout the harbour. During these blooms, the B.O.D. may reach as high as 31.2 mg/l (measured at station 4 on December 7, 1972 during a red tide produced by Gymnodinium splendens) which is several times more than the average values, even for Hunts Bay.

As with most other parameters, the B.O.D. at station 1 (Outer Harbour), station 3 (Hunts Bay) and station 4 (Inner Harbour) are the most variable, especially at the surface. At all these stations, the change in B.O.D. after rains is immediate and dramatic while at stations 5 and 7 in the Inner Harbour, it is delayed and less pronounced. Furthermore, at stations 1 and 4, there is the added factor of tidal exchange between open-sea and harbour waters which, especially during spring tides, may result in considerable changes in water quality at flood and ebb tides. Thus, station 4 in particular, which normally has a high B.O.D. due to run-off, waste discharges and plankton blooms may, under certain tide conditions, become quite clean and show a low B.O.D. On one such occasion (27th September, 1974), extreme spring tides accompanied by unusually calm weather resulted in a B.O.D. change at station 4 of from 6.2 to 2.3 mg/l within a single tidal cycle. While the higher value is fairly typical of harbour water, the lower value is only slightly above the average value of 2.0 mg/l obtained for open-sea water near Lime Cay.

Certain stations around the periphery of the harbour showed similar or even higher surface B.O.D. values than in Hunts Bay and the Inner Harbour. For example, the B.O.D. in Dawkins Pond during fairly normal conditions was measured at 7.2 mg/l while, during one of its frequent red tides, the B.O.D. rose to 19.8 mg/l. Other high values obtained were at Newport West (5.5 - 15.5 mg/l), Tivoli (7.2 - 39.3 mg/l), and Newport East (7.2 - 48.0 mg/l). Both the Tivoli and Newport East stations are marked by discharges of high B.O.D. wastes including sewage, soap and detergent wastes, and slaughterhouse wastes.

8. NUTRIENTS

Inorganic nutrients in the form of nitrates plus nitrites ($\text{NO}_3 + \text{NO}_2 - \text{N}$), phosphates ($\text{PO}_4 - \text{P}$) and silicates ($\text{SiO}_4 - \text{Si}$) were monitored routinely in Kingston Harbour commencing in November, 1971. In addition, nitrites ($\text{NO}_2 - \text{N}$) and ammonia ($\text{NH}_4 - \text{N}$) were also screened, but it was found that their concentrations were usually so low as to be below the level at which the methods employed could give satisfactory results. Hence, they were not measured routinely.

The nutrient monitoring has been over two periods. The first period was from November 1971 to October 1972 when 11 stations were occupied, sometimes on a fortnightly basis. Samples during this time were taken at 3 metre depth intervals and then mixed in equal proportions so as to produce one integrated sample for each station. Occasionally, however, a few profile measurements were made during this time. Then, in November 1972, profile measurements were commenced on a regular basis and samples were taken at 5 metre depth intervals instead of 3 metre intervals. The number of stations was also reduced from 11 to 5 and the frequency of sampling set at once a month. This second period of sampling (November 1972 to April 1975) was marked by two outstanding problems. One was the complete absence of sampling for 6 months (February to July, 1974) during which no boats were available, and the second was the unreliability of most of the nitrate + nitrite data due to filter paper interferences and lack of proper sample preservation. As a result, good routine data for this period only exist for the phosphates and silicates.

In order to analyse and compare the results from the two sampling periods, the data have been handled in a number of ways. In the first place, data from two twelve month periods have been extracted from the rest for all determinations of means and ranges. These periods are as follows:-

- (i) November 1971 to October 1972; and
- (ii) May to November, 1973 and December 1974 to April, 1975.

The second twelve month period is the same as that used for most other parameters in this water quality study. However, as mentioned above, there are no routine nitrate + nitrite data for this period. Nitrate + nitrite data are also missing for two months in the first period.

Secondly, the profile data obtained for each station during the second period have been combined so as to give one integrated measurement per station per month. Otherwise, these data would not be comparable with those from the first period during which the samples from all depths were mixed.

And thirdly, only the data obtained for the 5 stations occupied throughout the entire study (i.e. stations 1, 3, 4, 5 & 7) have been used for purposes of comparison.

The data thus arranged are presented in Tables 9, 10 and 11 and illustrated in Figure 20.

Nitrates + Nitrites

Nitrate + nitrite concentrations at the five stations during 1971 - 72 ranged from an average of 1.47 microgram atoms per litre ($\mu\text{ga}/\text{l}$) at station 1 in the Outer Harbour to 2.02 $\mu\text{ga}/\text{l}$ at station 3 in Hunts Bay. The Inner Harbour stations showed intermediate values of 1.66 $\mu\text{ga}/\text{l}$ at station 4, 1.99 $\mu\text{ga}/\text{l}$ at station 5, and 1.59 $\mu\text{ga}/\text{l}$ at station 7. The absolute highest value was 4.75 $\mu\text{ga}/\text{l}$ in Hunts Bay and the lowest was 0.10 $\mu\text{ga}/\text{l}$ in the Outer Harbour. These average and absolute values indicate a fairly consistent pattern in which Hunts Bay has the highest nitrate + nitrite concentrations, the Outer Harbour has the lowest, and the Inner Harbour is intermediate. However, the range of concentrations is quite small and there is only a 37% difference between Hunts Bay and the Outer Harbour, unlike the other nutrients discussed below.

All stations showed a peak in concentration during the rainy season. However, except in Hunts Bay, this peak was not as distinct as might be expected, and may be due to the fact that the rainy periods in 1971 - 72 were not as pronounced as usual. Further indication of this will be seen during discussion of the other nutrients where it becomes clear that the rains in the 1973 - 75 period had a far more pronounced effect than in the 1971 - 72 period.

It is of interest to note that station 5 in the Inner Harbour showed almost as high a nitrate + nitrite concentration as Hunts Bay although it is quite removed from Hunts Bay and separated from it by station 4 which did not show a similar high concentration. This would suggest that nitrate + nitrite concentration at station 5 was at least partly influenced by factors other than run-off in Hunts Bay.

Table 9: The Nitrate + Nitrite - N values in microgram atoms per litre ($\mu\text{ga/l}$) for integrated samples from the 5 monitoring stations for the period November 1971 to October 1972.

Date	Station 1	Station 3	Station 4	Station 5	Station 7
18.11.71	3.75	4.75	3.00	2.90	3.00
3.12.71	0.82	0.97	0.87	0.90	0.92
27.1.72	-	-	-	-	-
24.2.72	-	-	-	-	-
24.3.72	2.22	2.50	1.85	2.70	0.60
20.4.72	1.50	1.80	1.95	1.15	1.55
18.5.72	0.10	0.15	1.42	1.40	0.25
29.6.72	1.29	2.75	1.30	2.09	1.75
13.7.72	0.92	0.40	0.90	2.07	1.90
24.8.72	1.54	2.87	1.90	2.50	2.24
28.9.72	2.00	2.60	2.30	1.60	2.15
20.10.72	0.55	1.40	1.10	2.57	1.50
AVG.	1.47	2.02	1.66	1.99	1.59
MAX.	3.75	4.75	3.00	2.90	3.00
MIN.	0.10	0.15	0.87	0.90	0.25

Phosphates

The phosphate concentrations in 1971 - 72 and 1973 - 75 showed a similar distribution pattern as the nitrates + nitrites. That is, Hunts Bay was highest (1.49 and 22.40 $\mu\text{g}/\text{l}$), the Outer Harbour was lowest (0.31 and 0.42 $\mu\text{g}/\text{l}$) and the Inner Harbour stations were intermediate (.54 and .68 $\mu\text{g}/\text{l}$ for station 5) (See Table 14). However, the range in values was a great deal more than for the nitrates + nitrites and, in 1971 - 72, the difference between the Outer Harbour and Hunts Bay was nearly 400%. In 1973 - 75, the difference was very much greater.

Generally, the highest values were recorded during the rainy months of September, October and November while the lowest values were in the dry months of January, February and July. However, this seasonality was much more pronounced during the 1973 - 75 sampling period than during the 1971 - 72 period, and was most marked in Hunts Bay and at station 7 in the Inner Harbour (See Figs. 20.2 and 5).

All stations showed a significant increase in phosphate concentrations in 1973 - 75 over 1971 - 72. For example, the twelve month average for Hunts Bay rose from 1.49 $\mu\text{g}/\text{l}$ to 4.63 $\mu\text{g}/\text{l}$. However, this great difference was due largely to one extremely high value of 40.25 $\mu\text{g}/\text{l}$ obtained soon after an exceptionally heavy rainstorm. If we ignore this particular value, the eleven month average is reduced to 1.39 $\mu\text{g}/\text{l}$ which, however, is still 24% more than the 1971 - 72 average if the equivalent maximum value is ignored.

Table 10 (a): The Phosphate - P values in microgram atoms per litre ($\mu\text{g}/\text{l}$) for integrated samples from the 5 monitoring stations for the period November 1971 - October 1972.

Date	Station 1	Station 3	Station 4	Station 5	Station 7
18.11.71	0.70	5.50	0.90	0.70	1.00
3.12.71	0.55	3.25	0.77	0.80	1.10
27.1.72	0.67	1.67	0.70	0.65	0.60
24.2.72	0.50	0.65	0.55	0.69	0.90
24.3.72	0.60	0.98	0.66	0.88	0.89
20.4.72	0.42	0.35	0.40	0.60	1.06
18.5.72	0.19	0.90	0.40	0.20	0.31
29.6.72	0.21	1.27	0.60	0.49	0.72
13.7.72	0.02	0.33	0.14	0.06	0.34
24.8.72	0.15	0.60	0.38	0.51	0.80
28.9.72	0.30	1.22	0.80	0.75	0.55
20.10.72	0.07	1.15	0.16	0.20	0.50
AVG.	0.31	1.49	0.54	0.54	0.73
MAX.	0.70	5.50	0.90	0.88	1.10
MIN.	0.02	0.35	0.16	0.06	0.31

Table 10 (b): The Phosphate-P values in microgram atoms per litre ($\mu\text{ga/l}$) for integrated samples from the 5 monitoring stations for the periods May to November 1973 and December 1974 to April 1975.

Date	Station 1	Station 3	Station 4	Station 5	Station 7
10.5.73	0.55	0.40	0.69	1.02	1.45
8.6.73	0.30	0.69	0.43	0.41	0.83
12.7.73	0.72	1.13	0.55	0.75	0.80
10.8.73	0.43	1.28	0.82	0.79	0.73
7.9.73	0.63	1.92	0.74	0.62	0.73
4.10.73	0.49	2.68	0.77	1.24	1.30
16.11.73	0.57	2.17	0.62	0.89	1.98
2.12.74	0.44	40.25	1.30	0.62	0.88
16.1.75	0.23	1.86	0.40	0.25	0.38
8.2.75	0.18	0.38	0.44	0.48	1.28
4.3.75	0.18	0.96	0.60	0.62	1.30
10.4.75	0.32	1.84	1.54	0.46	0.95
AVG.	0.42	4.63	0.74	0.68	1.05
MAX.	0.72	40.25	1.54	1.24	1.98
MIN.	0.18	0.38	0.40	0.25	0.38

Station 7 showed the next highest increase in 1973 - 75 over 1971 - 72 with a rise from 0.73 $\mu\text{g}/\text{l}$ to 1.05 $\mu\text{g}/\text{l}$. However, this increase cannot be attributed to a single value or set of values since most measurements over the twelve month period were in excess of the 1971 - 72 levels (See Fig. 20.5). The same is true for all the other stations although the increases were smaller. Even station 1 in the Outer Harbour which has the lowest concentration and shows the least effect from rains had an increase of 35% over the two periods from 0.31 to 0.42 $\mu\text{g}/\text{l}$. These data therefore indicate strongly that there was a general increase in phosphate concentrations over the two sampling periods which cannot be attributed entirely to seasonal rains.

Silicates

The distribution of silicates in Kingston Harbour is very similar to those of other nutrients. During both sampling periods, Hunts Bay consistently had the highest concentrations of silicates (Avg. 22.74 and 34.00 $\mu\text{g}/\text{l}$) while the Outer Harbour had the lowest (Avg. 3.69 and 6.17 $\mu\text{g}/\text{l}$). Station 7 in the Inner Harbour was the second highest both times with average values of 6.64 and 11.02 $\mu\text{g}/\text{l}$, while stations 4 and 5 were somewhat lower (See Table 11). This spread of values is very similar to that of the phosphate concentration with Hunts Bay the highest, showing a difference over the Outer Harbour, the lowest, of more than 400 % (Fig. 20.1-20.5).

The seasonal distribution of silicates is more pronounced than that of any other nutrient and reflects the rainfall pattern most strongly (Fig. 20). Highest concentrations were in October, November and December while the lowest concentrations were in January, February and July. A minor peak occurred in Hunts Bay in May and June, 1972, following brief seasonal rains. Hunts

Bay and the Inner Harbour showed the pattern most clearly, while the Outer Harbour less so.

As with phosphates, the 1973 - 75 silicate data showed an increase in concentrations over 1971 - 72 (Tables 11a and b). The greatest increases were at stations 4 and 1 which were directly affected by surface run-off following rains. However, none of these stations showed as high silicate concentrations as station 7 in the Inner Harbour, which is surprising since this station is the furthest removed from the major sources of run-off. Indeed, next to Hunts Bay, station 7 had the highest phosphate concentrations as well, while the adjacent station 5 had the highest nitrate + nitrite concentrations. This all seems to suggest that these two stations must have one or more sources of nutrients other than or in addition to stormwater run-off via Hunts Bay. If this is so, we need to examine what these sources might be and one way of doing so is to look at the vertical distribution pattern in the water column.

Monthly profile measurements of phosphates and silicates exist for all stations for the 1973 - 75 sampling period while there are occasional measurements for the 1971 - 72 period. They help to provide at a glance some indication of the factors contributing to nutrient enrichment. For convenience, we shall consider only surface and bottom concentrations first (See Tables 12 and 13 and Fig. 21).

These data show that at Hunts Bay phosphate and silicate concentrations were always higher at the surface than at the bottom and, in fact, the levels

Table 11 (a): The Silicate - Si values in microgram atoms per litre ($\mu\text{ga/l}$) for integrated samples from the 5 monitoring stations for the period November 1971 to October 1972.

Date	Station 1	Station 3	Station 4	Station 5	Station 7
18.11.71	2.00	55.00	5.00	4.00	11.00
3.12.71	7.50	42.75	8.25	9.75	12.25
27.1.72	4.50	19.80	5.00	3.00	3.00
24.2.72	4.10	5.50	3.00	4.35	5.70
24.3.72	10.75	18.00	6.25	10.00	9.25
20.4.72	4.00	2.50	2.90	6.10	10.95
18.5.72	2.00	22.00	2.20	0.00	0.20
29.6.72	2.65	16.70	5.90	3.80	5.95
13.7.72	1.00	7.70	0.00	0.80	4.00
24.8.72	1.00	19.75	4.80	7.20	8.25
28.9.72	2.90	20.75	6.10	4.00	3.85
20.10.72	1.90	42.50	5.50	6.00	5.35
AVG.	3.69	22.74	4.74	4.91	6.64
MAX.	10.75	55.00	8.25	10.00	12.25
MIN.	1.00	2.50	0.00	0.00	0.20

Table 11 (b): The Silicate - Si values in microgram atoms per litre ($\mu\text{ga/l}$) for integrated samples from the 5 monitoring stations for the periods May to November, 1973 and December 1974 to April 1975.

Date	Station 1	Station 3	Station 4	Station 5	Station 7
10.5.73	6.25	2.70	4.62	7.32	10.32
8.6.73	2.57	6.65	3.00	7.07	11.74
12.7.73	8.50	8.85	6.52	7.30	6.96
10.8.73	7.27	26.10	12.42	9.05	8.10
7.9.73	9.62	39.20	9.77	7.12	12.00
4.10.73	9.92	58.00	12.62	15.72	15.96
16.11.73	11.15	85.70	14.22	16.52	26.06
2.12.74	6.22	117.55	30.87	6.95	10.22
16.1.75	3.70	35.65	3.80	0.67	2.24
8.2.75	4.35	5.95	5.00	5.00	10.76
4.3.75	3.92	11.15	5.90	7.57	10.32
10.4.75	2.67	10.60	8.07	2.97	7.66
AVG.	6.17	34.00	9.73	7.77	11.02
MAX.	11.15	117.55	30.87	16.52	26.06
MIN.	2.57	2.70	3.00	0.67	2.24

le 12: The surface and bottom values for Phosphate - P concentrations in microgram atoms per litre ($\mu\text{g}/\text{l}$) at the 5 monitoring stations for the periods May to November 1973, and December 1974 to April 1975.

Date	(1)		(3)		(4)		(5)		(7)	
	Sur.	Bot.	Sur.	Bot.	Sur.	Bot.	Sur.	Bot.	Sur.	Bot.
10.5.73	0.40	0.79	0.40	0.41	0.62	0.88	0.79	1.32	1.33	1.45
8.6.73	0.26	0.40	0.96	0.43	0.17	0.91	0.44	0.39	0.60	1.05
12.7.73	0.69	0.80	1.25	1.02	0.50	0.60	0.70	0.78	0.80	0.78
10.8.73	0.36	0.70	1.52	1.05	0.80	0.93	0.80	0.67	0.69	0.72
7.9.73	0.43	0.85	3.25	0.60	0.30	1.40	0.46	0.65	0.40	1.75
4.10.73	0.60	0.60	4.20	1.17	1.15	0.70	0.60	2.95	0.61	3.25
16.11.73	0.57	0.73	3.45	0.90	0.60	0.95	0.50	1.10	0.50	4.50
2.12.74	0.60	0.51	70.00	1.05	3.18	0.80	0.50	1.10	0.60	1.61
16.1.75	0.29	0.29	2.85	0.87	0.39	0.60	0.20	0.31	0.35	0.49
8.2.75	0.19	0.23	0.32	0.44	0.51	0.40	0.41	0.80	0.19	2.52
4.3.75	0.20	0.18	1.37	0.55	0.40	1.20	0.40	0.80	0.40	0.78
10.4.75	0.40	0.42	2.09	1.60	1.60	1.30	0.40	0.44	0.48	2.13
AVG.	0.41	0.54	7.63	0.84	0.82	0.89	0.51	0.96	0.58	1.75
MAX.	0.69	0.85	70.00	1.17	3.18	1.40	0.80	2.95	1.33	4.50
MIN.	0.19	0.18	0.32	0.41	0.17	0.40	0.20	0.31	0.35	0.49

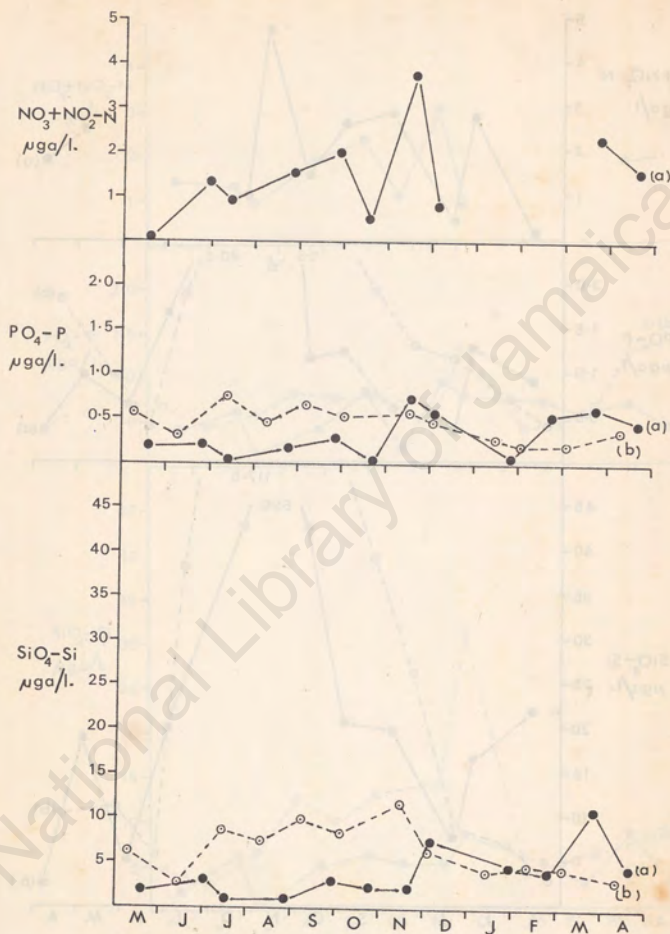


Figure 20 (20.1 - 20.5)

Monthly nutrient concentrations at the 5 monitoring stations during the two sampling periods: (a) 1971 - 72; (b) 1973 - 75. Note that the order of readings has been rearranged for easy comparison.

Table 13: The surface and bottom values for Silicate - Si concentrations in microgram atoms per litre ($\mu\text{ga/l}$) at the 5 monitoring stations for the periods May to November 1973 and December 1974 to April 1975.

Date	(1)		(3)		(4)		(5)		(7)	
	Sur.	Bot.	Sur.	Bot.	Sur.	Bot.	Sur.	Bot.	Sur.	Bot.
10.5.73	5.4	7.8	2.9	2.5	5.1	5.3	5.4	10.5	9.3	10.1
8.6.73	1.8	4.9	8.8	4.5	1.2	6.9	7.1	7.2	11.5	12.0
12.7.73	8.0	9.4	10.9	6.8	6.9	6.4	7.8	5.9	6.5	7.1
10.8.73	8.3	8.1	38.8	13.4	16.8	10.5	10.2	6.6	8.0	7.8
7.9.73	5.9	13.4	70.0	8.4	5.0	16.5	4.0	9.3	5.6	28.0
4.10.73	12.6	7.3	100.0	16.0	22.4	9.6	9.0	29.2	9.0	32.5
16.11.73	12.0	13.6	155.0	16.4	17.0	17.2	14.0	14.7	13.6	45.0
2.12.74	8.6	7.3	219.0	16.1	99.0	11.5	6.5	14.8	4.5	21.7
16.1.75	3.9	4.0	62.4	8.9	3.0	7.0	1.0	0.7	2.0	1.2
8.2.75	4.0	5.6	7.9	4.0	4.6	5.0	5.0	8.0	1.8	21.0
4.3.75	3.8	4.0	18.3	4.0	6.0	8.2	5.3	9.0	4.3	9.0
10.4.75	3.5	3.0	12.2	9.0	8.8	9.0	3.0	2.9	2.0	22.2
AVG.	6.48	7.36	58.85	9.16	16.31	9.42	6.52	9.9	6.50	16.55
MAX.	12.6	13.6	219.0	16.4	99.0	17.2	14.0	29.2	13.6	45.0
MIN.	1.8	3.0	2.9	2.5	1.2	5.0	1.0	0.7	1.8	1.2

2. Station 3

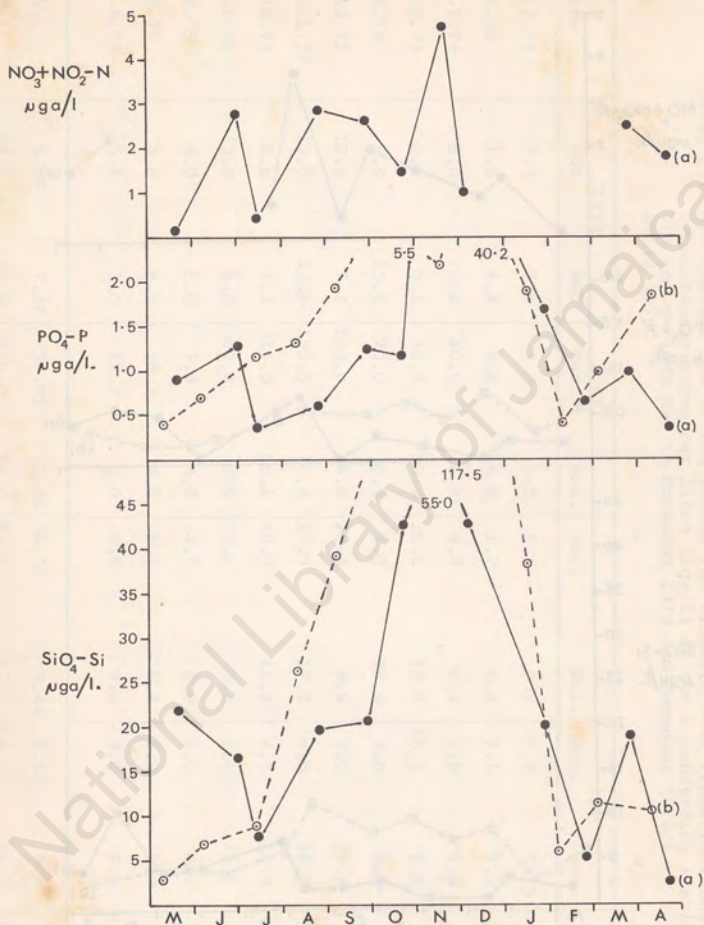


Figure 20 (20.1 - 20.5)

Monthly nutrient concentrations at the 5 monitoring stations during the two sampling periods: (a) 1971 - 72; (b) 1973 - 75. Note that the order of readings has been rearranged for easy comparison.

3. Station 4

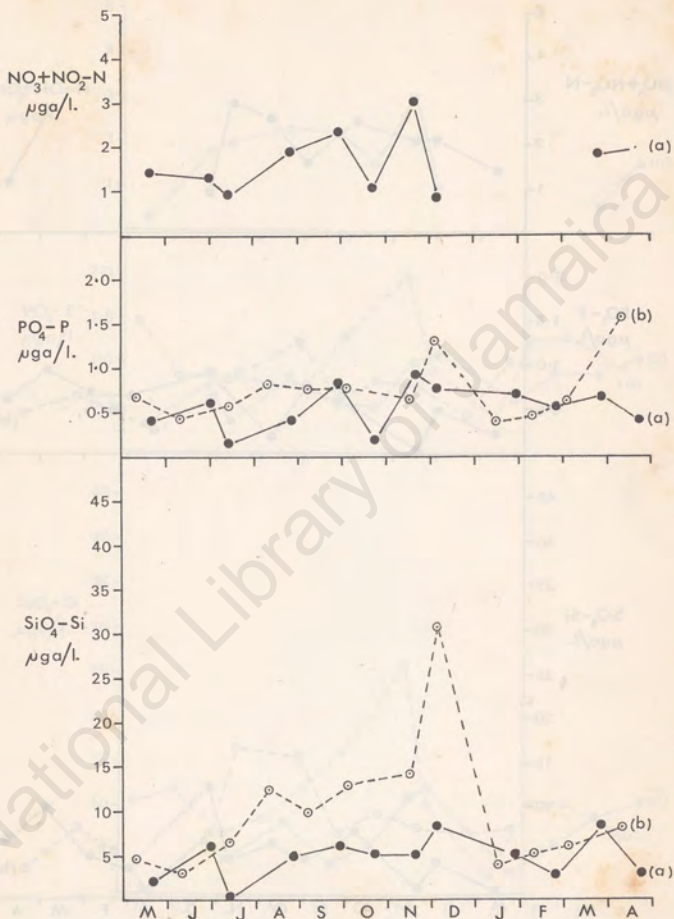


Figure 20 (20.1 - 20.5)

— 1971-72
 - - - 1973-75

Monthly nutrient concentrations at the 5 monitoring stations during the two sampling periods: (a) 1971 - 72; (b) 1973 - 75. Note that the order of readings has been rearranged for easy comparison.

4. Station 5

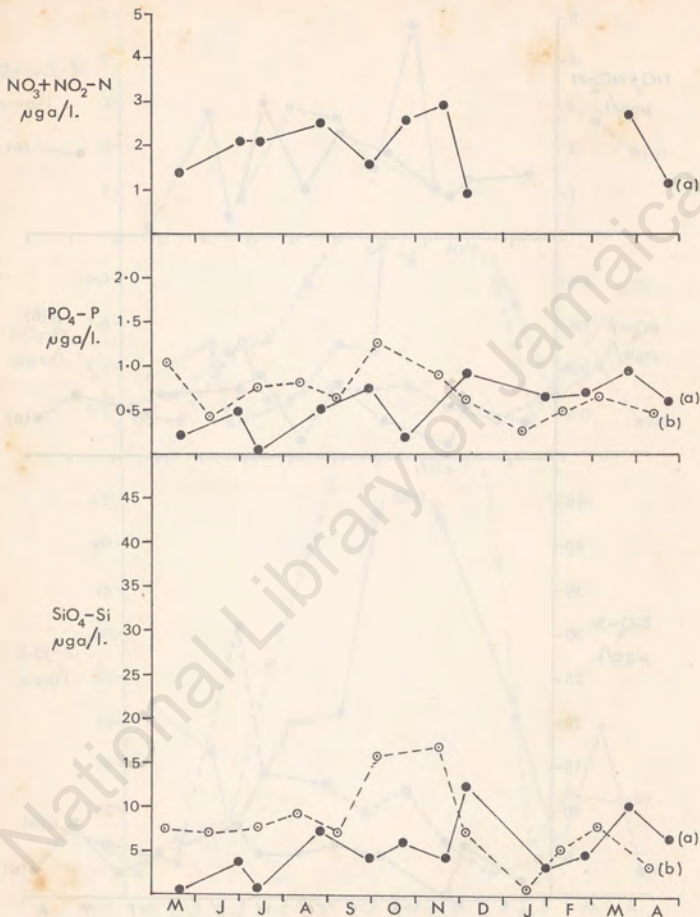


Figure 20 (20.1 - 20.5)

Monthly nutrient concentrations at the 5 monitoring stations during the two sampling periods: (a) 1971 - 72; (b) 1973 - 75. Note that the order of readings has been rearranged for easy comparison.

●—● 1971-72
○---○ 1973-75

5. Station 7

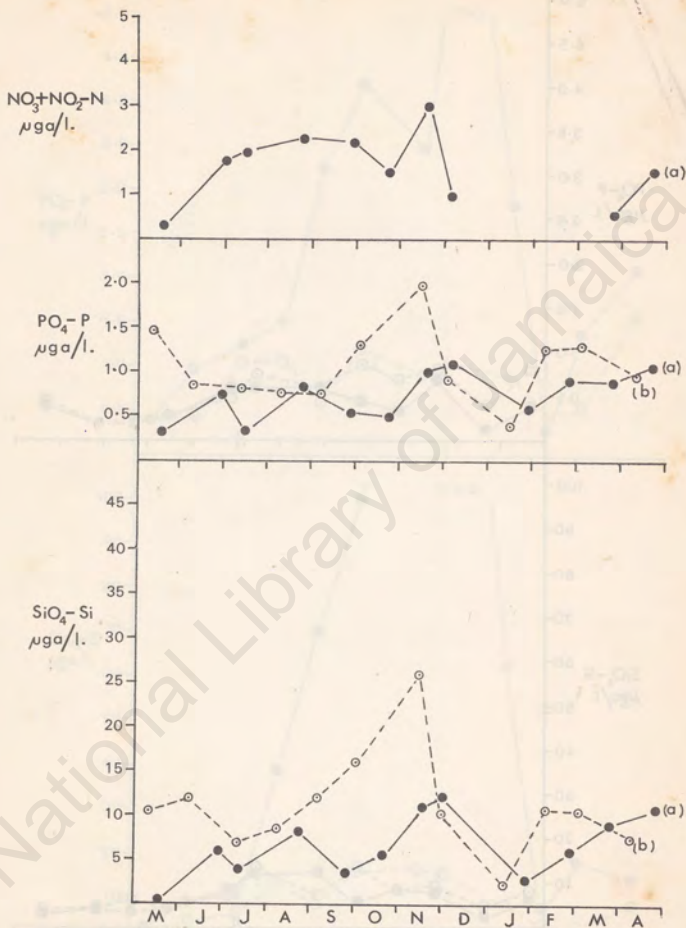


Figure 20 (20.1 - 20.5)

Monthly nutrient concentrations at the 5 monitoring stations during the two sampling periods: (a) 1971 - 72; (b) 1973 - 75. Note that the order of readings has been rearranged for easy comparison.

1. Station 1

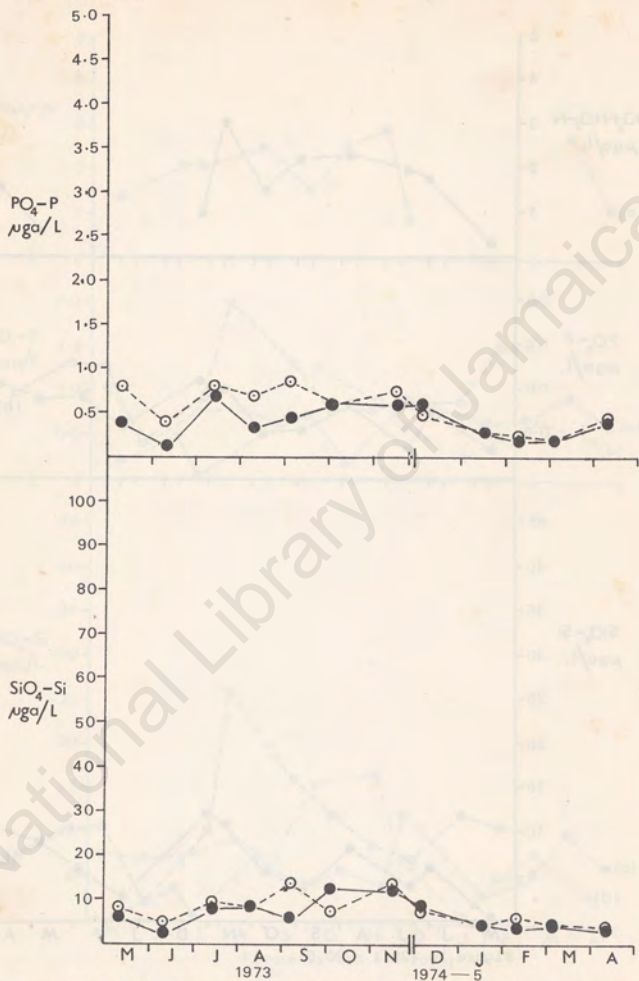


Figure 21 (21.1 - 21.5)

Monthly nutrient values for surface and bottom at the 5 monitoring stations for the 1973 - 75 sampling period.

● — ● Surface
○ — ○ Bottom

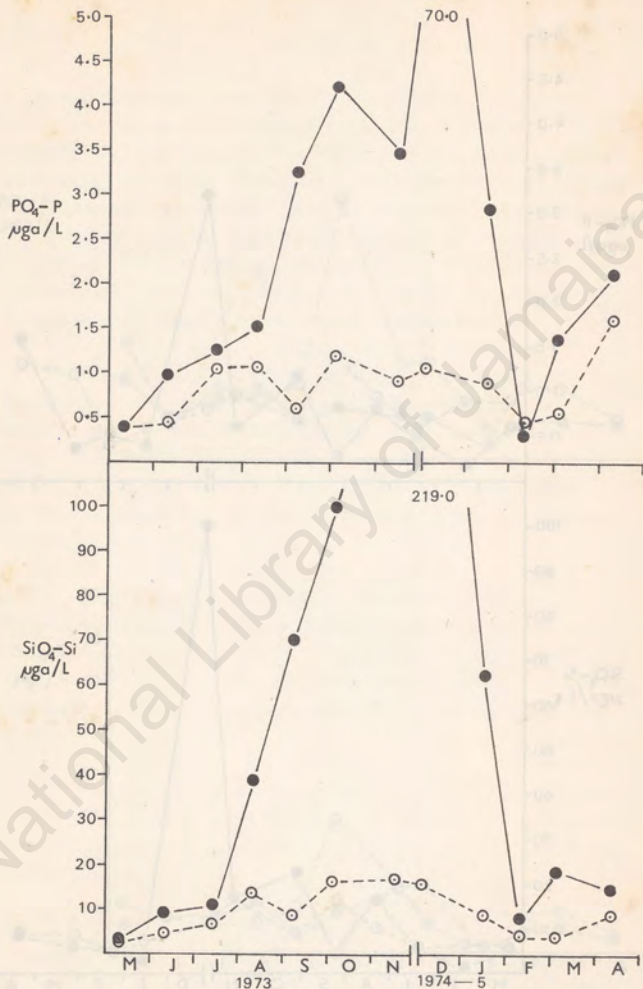


Figure 21 (21.1 - 21.5)

●—● Surface
 ○—○ Bottom

Monthly nutrient values for surface and bottom at the 5 monitoring stations for the 1973 - 75 sampling period.

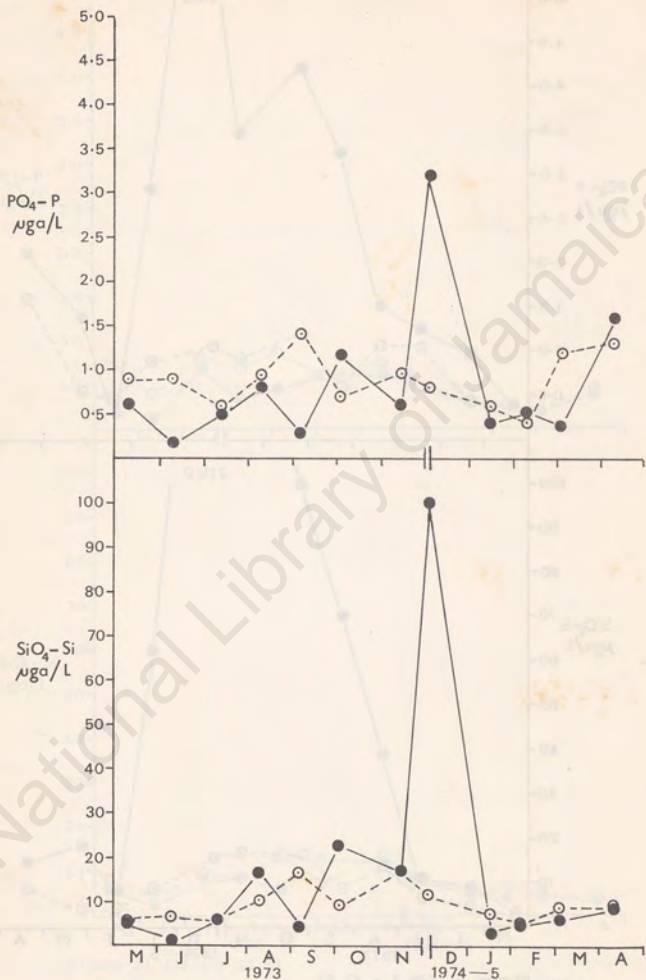


Figure 21 (21.1 - 21.5)

Monthly nutrient values for surface and bottom at the 5 monitoring stations for the 1973 - 75 sampling period.

● — ● Surface
○ — ○ Bottom

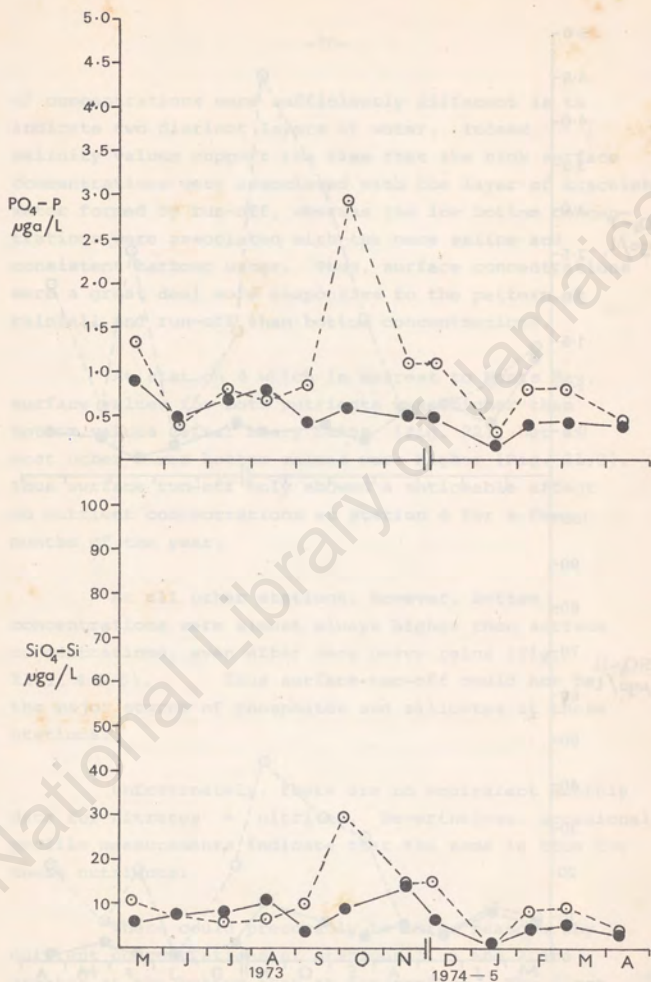


Figure 21 (21.1 - 21.5)

Monthly nutrient values for surface and bottom at the 5 monitoring stations for the 1973 - 75 sampling period.

● — ● Surface
○ — ○ Bottom

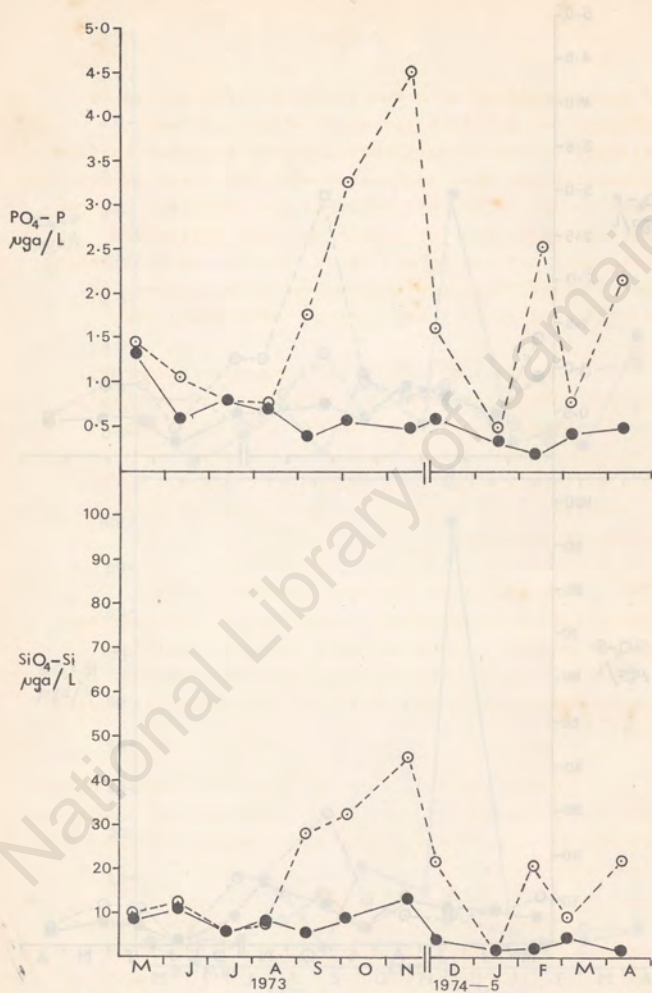


Figure 21 (21.1 - 21.5)

Monthly nutrient values for surface and bottom at the 5 monitoring stations for the 1973 - 75 sampling period.

● — ● Surface
○ — ○ Bottom

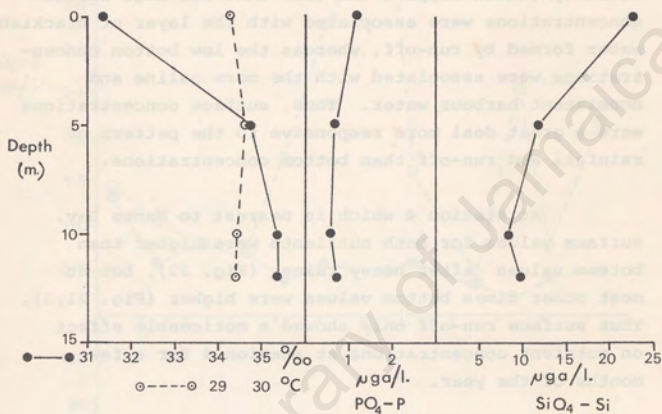


Figure 22

Phosphate and silicate profiles at station 4 following heavy run-off, showing the higher concentrations at the surface.

of concentrations were sufficiently different as to indicate two distinct layers of water. Indeed, salinity values support the view that the high surface concentrations were associated with the layer of brackish water formed by run-off, whereas the low bottom concentrations were associated with the more saline and consistent harbour water. Thus, surface concentrations were a great deal more responsive to the pattern of rainfall and run-off than bottom concentrations.

At station 4 which is nearest to Hunts Bay, surface values for both nutrients were higher than bottom values after heavy rains (Fig. 22), but at most other times bottom values were higher (Fig. 21.3). Thus surface run-off only showed a noticeable effect on nutrient concentrations at station 4 for a few months of the year.

At all other stations, however, bottom concentrations were almost always higher than surface concentrations, even after very heavy rains (Fig. 21.1, 4 & 5). Thus surface run-off could not be the major source of phosphates and silicates at these stations.

Unfortunately, there are no equivalent monthly data for nitrates + nitrites. Nevertheless, occasional profile measurements indicate that the same is true for these nutrients.

There could presumably be three reasons why nutrient concentrations at stations 1, 5 and 7 are greater at the bottom than at the surface. The first

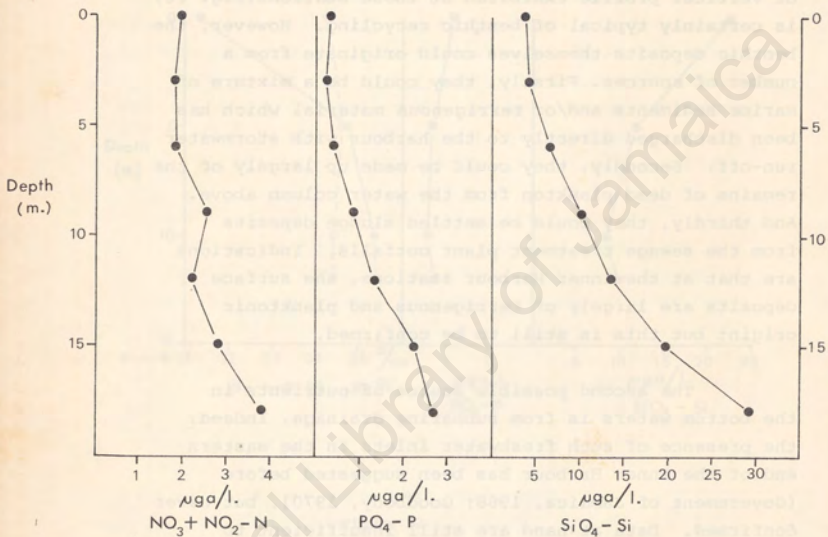


Figure 23

Nutrient profiles at station 7,
showing the normally higher con-
centrations near the bottom.

and most obvious is that these nutrients are generated by the benthic deposits and recycled to the water column under suitable conditions. Indeed this is the major source of nutrients in the open sea, and the kind of vertical profile exhibited at these stations (Fig. 23) is certainly typical of benthic recycling. However, the benthic deposits themselves could originate from a number of sources. Firstly, they could be a mixture of marine sediments and/or terrigenous material which has been discharged directly to the harbour with stormwater run-off. Secondly, they could be made up largely of the remains of dead plankton from the water column above. And thirdly, they could be settled sludge deposits from the sewage treatment plant outfalls. Indications are that at the Inner Harbour stations, the surface deposits are largely of terrigenous and planktonic origin; but this is still to be confirmed.

The second possible source of nutrients in the bottom waters is from submarine drainage. Indeed, the presence of such freshwater inlets in the eastern end of the Inner Harbour has been suggested before (Government of Jamaica, 1968; Goodbody, 1970), but never confirmed. Data at hand are still insufficient to demonstrate conclusively that they exist although evidence from the nutrient data is very strong indeed. This evidence may be stated as follows. Firstly, the levels of nutrients in the bottom water at stations 5 and 7 show a seasonality which is identical with the rainfall pattern and which is much more pronounced than that of the surface nutrients (See Fig. 21. 4 & 5). Furthermore, following each major rainfall, the bottom nutrient concentrations at these stations show a very

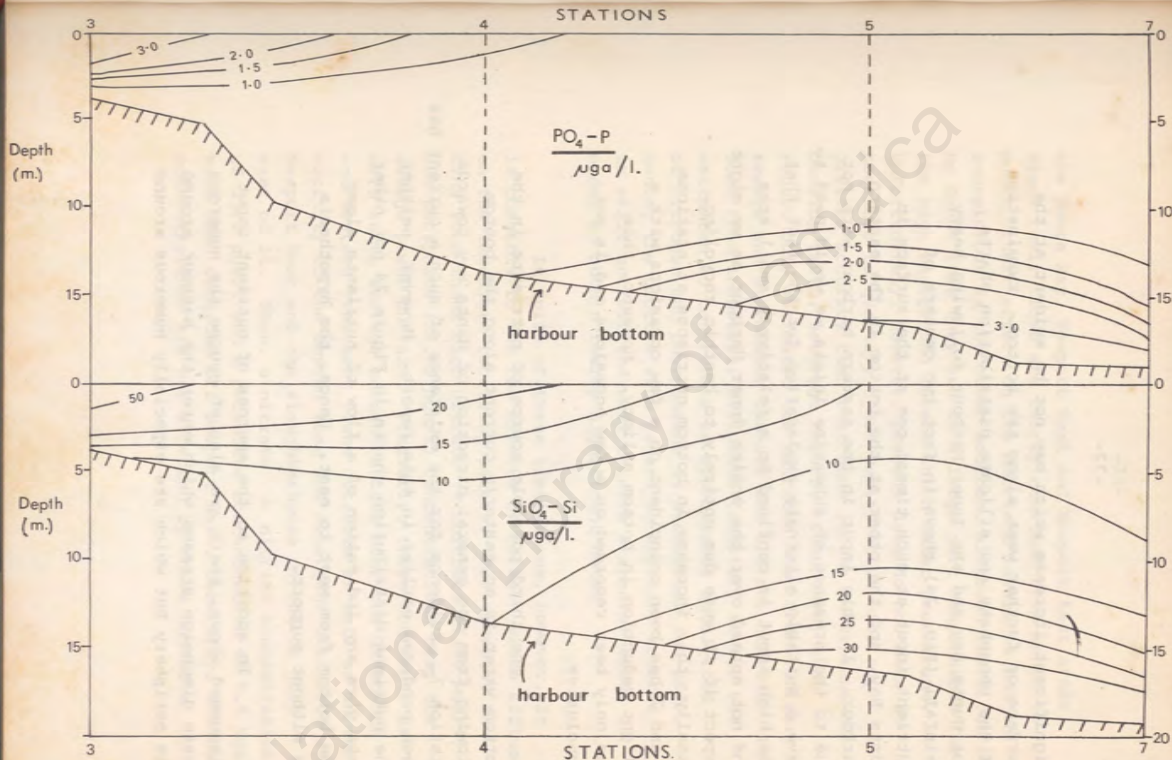


Figure 24

The distribution of phosphates and silicates along a transect from station 3 in Hunts Bay to station 7 in the Inner Harbour after heavy rains, showing the input of these nutrients at the surface in Hunts Bay and at the bottom in the eastern harbour. The contours are in $\mu\text{g/l.}$

significant increase which may not be evident at the surface or further west along the bottom. Examination of the phosphate and silicate distribution charts for Hunts Bay and the Inner Harbour following heavy rainfall (Fig. 24) shows in fact two centers of nutrient input at such times; one at the surface in Hunts Bay, and the other at the bottom in the eastern harbour. If this input in the eastern harbour were not due to the presence of submarine inlets we would need to have a suitable alternate explanation for the fact that the high input is confined to a relatively small area and not spread over the entire Inner Harbour as we might expect if it were due entirely to benthic recycling. Finally, this increase in bottom nutrients at stations 5 and 7 has been coincident on a few occasions with a slight reduction in bottom salinity. However, this has only been recorded on a few occasions and is not conclusive.

The third possible source of nutrients in the bottom water is an easterly current along the bottom flowing from the general direction of Hunts Bay towards station 7. Evidence for the existence of such a current has been produced earlier in this report. However, neither the nutrient distribution charts in Figure 24 nor other data give any indication of a flow of nutrients along the bottom from west to east. Hence, the hypothesis is without support.

In addition to the sources of nutrient input discussed above, there are also of course the numerous waste discharge streams which enter the harbour around its periphery but which are especially numerous around

the Hunts Bay, Newport West and Newport East areas. Since their flows are fairly constant from month to month, their effect on the nutrient levels is not as conspicuous as the other sources, although there can be no doubt that they are in a large part responsible for the high background levels which exist year-round. Unfortunately, however, present data do not make it possible to quantify their contribution with any greater accuracy than that done in the Government of Jamaica (1970) sewerage report. Even then, that report only estimated the nutrient load from sanitary sewage and stormwater run-off and did not consider the load from industrial effluents (sanitary sewage was estimated to contribute an approximate equal load of nitrogen and phosphorous as stormwater run-off). Hence, the picture with regard to effluent sources is still unclear and will require a special study in order to obtain really significant data.

In spite of these limitations, however, it is possible to see the effects of certain waste effluents on the immediate receiving waters. For example, Dawkins Pond shows high nitrate + nitrite ($6.20 \mu\text{ga}/1$) and phosphate ($11.65 \mu\text{ga}/1$) concentrations near the sewage plant outfall. Similarly, these nutrients are well above average concentrations near the Greenwich and Western treatment plant outfalls as well as in the vicinity of the Seprod soap and detergent discharge at Newport East and the slaughterhouse discharge just east of it. Thus, a nitrate + nitrite concentration of $13.2 \mu\text{ga}/1$ and a phosphate concentration of $9.5 \mu\text{ga}/1$ have been recorded off Newport East. Generally, silicate concentrations are not affected by these outfalls.

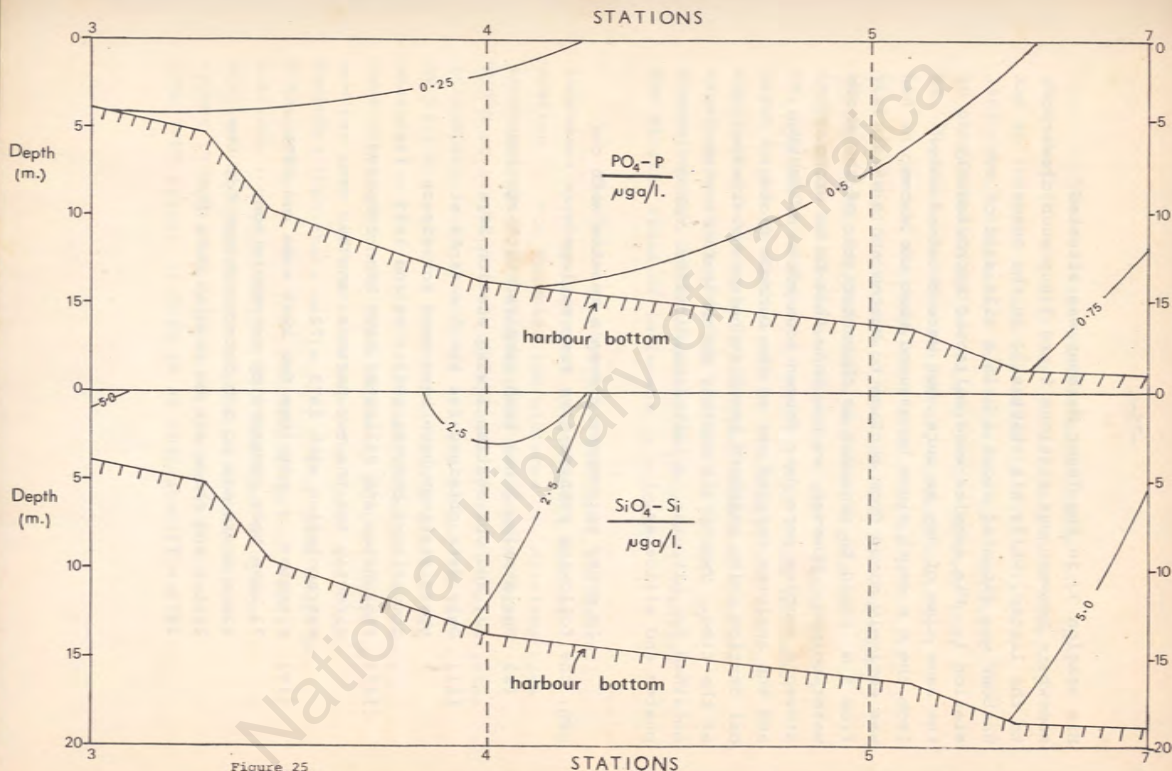


Figure 25

The distribution of phosphates and silicates along a transect from station 3 in Hunts Bay to station 7 in the Inner Harbour during the dry windy month of March. The contours are in $\mu\text{g/l}$.

One thing further needs to be considered in discussing nutrient distribution and this is the effect of wind and wave action. There can be no doubt that vertical mixing of nutrients in Kingston Harbour is accomplished mainly by wave action. Thus during the windy months of March to August, the water column is well mixed and the difference between surface and bottom nutrient concentrations is least for the year. (See Fig. 21). Furthermore, due to wind driven currents, horizontal mixing is also enhanced and the station differences are reduced. Thus, the entire harbour is more homogeneous than at any other time. Since nutrient concentrations are also about the lowest for the year at that time, the harbour may thus be said to exhibit its natural background nutrient conditions during these months (Fig. 25). This is in marked contrast to the situation which exists in September, October and November, when the concentrations are highest and both the horizontal and vertical differences are extreme (Fig. 24).

The question inevitably arises as to whether over the past several years there has been an increase or a decrease of nutrient concentrations in Kingston Harbour, and whether in fact there is over-enrichment of the system. In order to answer these, we need to refer to the earlier works of Steven (1965 & 1966) and compare the results then with the present. However, in doing so, we must take note of certain differences in the methods employed.

Steven (1965) examined two stations routinely in Kingston Harbour between July 1962 and June 1964.

His station 3J in the Inner Harbour was situated somewhere between our stations 5 and 7 but much closer to the latter, while his station 2J in the Outer Harbour was situated about a half a mile east of our station 1. His samples were collected approximately the same time of day as ours, but were obtained only from the 5 m depth since he assumed that the water was entirely mixed from surface to bottom and a sample from 5 m could be regarded as characteristic of the whole water column. However, we now know this to be wrong. Steven's samples were deep frozen soon after collection and the analyses carried out at the Bermuda Biological Station using standard bench techniques available at the time. Twenty six monthly determinations were obtained for nitrates + nitrites, nitrites, phosphates and silicates.

In order to compare Steven's results with our own, the following methods have been employed:

- (i) Our station 7 has been compared with station 3J, and our station 1 with station 2J;
- (ii) Only data obtained for the 5 m depth at these stations have been used for direct comparisons between 1962 - 64 and 1973 - 75;
- (iii) Phosphates and silicates have been compared directly for the two periods, and by extrapolation with 1971 - 72;
- (iv) Nitrates + nitrites for 1962 - 64 and 1971 - 72 have been compared by extrapolation, since there are no 5 m determinations for the latter and there are no regular data for 1973 - 75.

The data are summarised in Table 14. They show that for the nitrates + nitrites both stations had an increase in concentration in 1971 - 72 over 1962 - 64. Similarly, both stations had increases in phosphates in 1971 - 72 and 1973 - 75 over 1962 - 64. However, for the silicates, whereas station 1 had an overall increase from 1962 - 64 to 1973 - 75, station 7 had a decrease. Thus, in all but one case, the data indicate that there has been a general increase in nutrients at stations 1 and 7 since 1962 - 64. It could be argued, however, that these increases might be due to differences in the analytical methods employed and not to real changes. However, when one examines the 1971 - 72 and the 1973 - 75 data by themselves for which identical methods were employed, the similar trend of increases is evident.

The Table 14 data also show that the overall increases have been greater at station 1 than at station 7. For example, the nitrates + nitrites have increased by 46.1 % at station 1 as compared with 7.9 % at station 7; the phosphates by 450.0 % at station 1, compared with 234.8 % at station 7; and the silicates by 53.3 % at station 1 compared with a decrease at station 7. Thus it is clear that the major increases have occurred in the Outer Harbour, so that there is now far less difference between the Outer and Inner Harbours than there was in 1962 - 64. This could be interpreted to mean that the main effect of high nutrient inputs to the harbour has been to spread nutrient rich water over a wider area than before, rather than to merely increase concentrations in localised areas. If this is as indicated then it

Table 14: A comparison of nutrient concentrations at the 5 metre depth at stations 1 (Outer Harbour) and 7 (Inner Harbour) for the periods 1962 - 64 (Steven, 1965), 1971 - 72, and 1973 - 75. All measurements are in uga/l.

	<u>1962-64</u>	<u>1971-72</u>	<u>1973-75</u>	<u>Overall Increase</u>
Stn. 1: $\text{NO}_3 + \text{NO}_2 - \text{N}$	0.78	(1.14)	-	46.1%
$\text{PO}_4 - \text{P}$	0.08	(0.27)	0.36	450.0%
$\text{SiO}_4 - \text{Si}$	3.49	(3.20)	5.35	53.3%
Stn. 7: $\text{NO}_2 + \text{NO}_2 - \text{N}$	1.14	(1.23)	-	7.9%
$\text{PO}_4 - \text{P}$	0.23	(0.54)	0.77	234.8%
$\text{SiO}_4 - \text{Si}$	10.70	(3.65)	6.06	-43.4%

Data in parentheses were obtained by extrapolation from 4 profile measurements.

means that more and more of the harbour including the Outer Harbour is being affected by the existing nutrient discharges.

The final conclusion to be drawn from the data in Table 14 is that the phosphates have shown the greatest increase followed by the nitrates + nitrites (up to 1971 - 72) and then the silicates. However, since stormwater run-off is the major source of silicates and this nutrient has increased the least, the greater increases in phosphates and nitrates + nitrites must be due at least in part to causes other than increased run-off. These could be greater benthic recycling and/or increased waste discharges. Of these two, the latter is unquestionably true and is linked to the proliferation of domestic and industrial waste outfalls around the periphery of the harbour since the 1962 - 64 period. On the other hand, the increase if any in benthic recycling is uncertain.

Goodbody (1970) in a review of the biology of Kingston Harbour quoted Steven's (1965) data and concluded "It is clear...that Kingston Harbour is an area of exceptionally high biological productivity and that this high level is maintained by correspondingly high levels of available nutrients." He further drew attention to the increasing frequency of phytoplankton blooms in the harbour and noted the conclusion drawn by Steven (1966) that in a particular bloom he studied "nitrogen enrichment was a precondition of the bloom." Since this review, our data and observations have confirmed the high level of nutrients which exist in the harbour and the occurrence of exceptionally high nitrogen and phosphorus concentrations

within the area of phytoplankton blooms. For example, in one particular bloom in the Outer Harbour produced by the dinoflagellate Gymnodinium splendens, the average nitrate + nitrite concentration was 10.47 $\mu\text{g}/\text{l}$ and the average phosphate concentration 2.21 $\mu\text{g}/\text{l}$. In other words, the concentrations of those nutrients during the bloom (November, 1972) were nearly ten times the normal as defined by the 1971 - 72 averages at station 1.

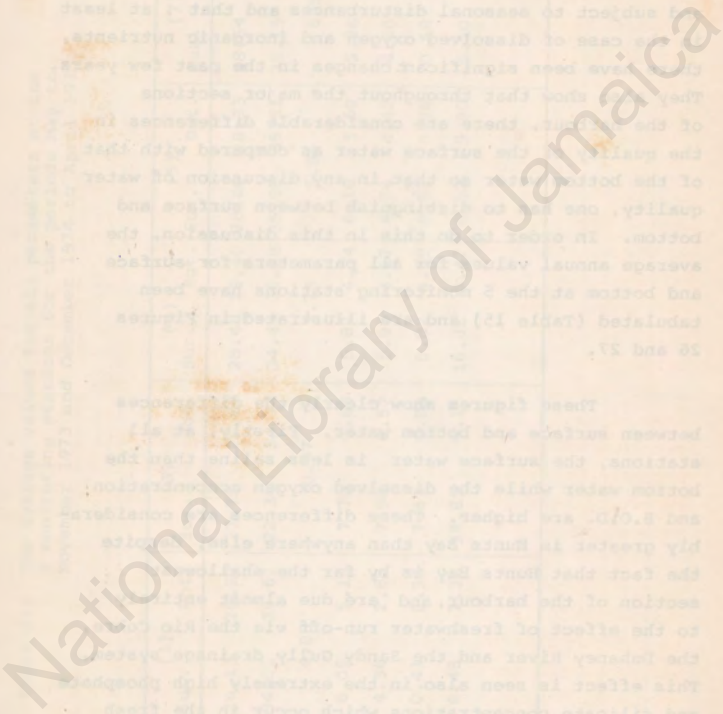
The occurrence of these exceptionally high nutrient concentrations in patches is not fully understood, nor are the mechanisms which trigger the onset of blooms. Nevertheless, it is known that blooms cannot occur without a certain high background level of nutrients, especially nitrogen, and that as a result of the blooms, the nutrients become depleted. These conditions have been described in detail by Steven (1966) for a bloom of the Inner Harbour and have now been observed during this study for blooms in all major sections of the harbour. Thus the role of nutrients not only in sustaining high primary production, but also in promoting phytoplankton blooms throughout Kingston Harbour is well established.

Grahame (1974) has concluded that the high nutrient inputs to Kingston Harbour are not deleterious to the zooplankton, but seem beneficial. However, he has suggested that the abundant development of the zooplankton may adversely affect the harbour benthos through contributing to deoxygenation of the bottom water. If this is so, and our data indicate that it is, then Kingston Harbour must be classified as

eutrophic or over-enriched and therefore in need of a reduction of nutrient levels in order to regain a proper balance throughout.

preceding sections provide a comparison of the water in Kingston Harbour. They reveal that the harbour system is subject to seasonal disturbances and that, at least in the case of dissolved oxygen and inorganic nutrients, there have been significant changes in the last few years. They show that throughout the major sections of the harbour, there are considerable differences in the quality of the surface water as compared with that of the bottom water in any discussion of water quality, one must be cognizant of the vertical gradient between surface and bottom. In order to do this in this discussion, the average annual values for all parameters for surface and bottom at the 5 monitoring stations have been calculated (Table 15) and illustrated in Figures 26 and 27.

These figures show that, in general, between surface and bottom water in the harbour, the surface water is better than the bottom water with the dissolved oxygen concentration and B.O.D. are higher. These differences are particularly marked in the section of the harbour, and due almost entirely to the effect of freshwater run-off via the Kingston River and the Sandy Bay drainage system. This effect is seen also in the extremely high phosphate and nitrate concentrations which occur in the fresh surface water of Humber Bay, as well as in the very low transparency. Thus the surface water is under



9. DISCUSSION

The water quality data discussed in the preceding sections provide a comprehensive picture of the state of the water in Kingston Harbour. They reveal, first of all, that the harbour system is complex and subject to seasonal disturbances and that, at least in the case of dissolved oxygen and inorganic nutrients, there have been significant changes in the past few years. They also show that throughout the major sections of the harbour, there are considerable differences in the quality of the surface water as compared with that of the bottom water so that in any discussion of water quality, one has to distinguish between surface and bottom. In order to do this in this discussion, the average annual values for all parameters for surface and bottom at the 5 monitoring stations have been tabulated (Table 15) and are illustrated in Figures 26 and 27.

These figures show clearly the differences between surface and bottom water. Firstly, at all stations, the surface water is less saline than the bottom water while the dissolved oxygen concentration and B.O.D. are higher. These differences are considerably greater in Hunts Bay than anywhere else, despite the fact that Hunts Bay is by far the shallowest section of the harbour, and are due almost entirely to the effect of freshwater run-off via the Rio Cobre, the Duhaney River and the Sandy Gully drainage system. This effect is seen also in the extremely high phosphate and silicate concentrations which occur in the fresh surface water of Hunts Bay, as well as in its very low transparency. Thus the Hunts Bay surface water is unique

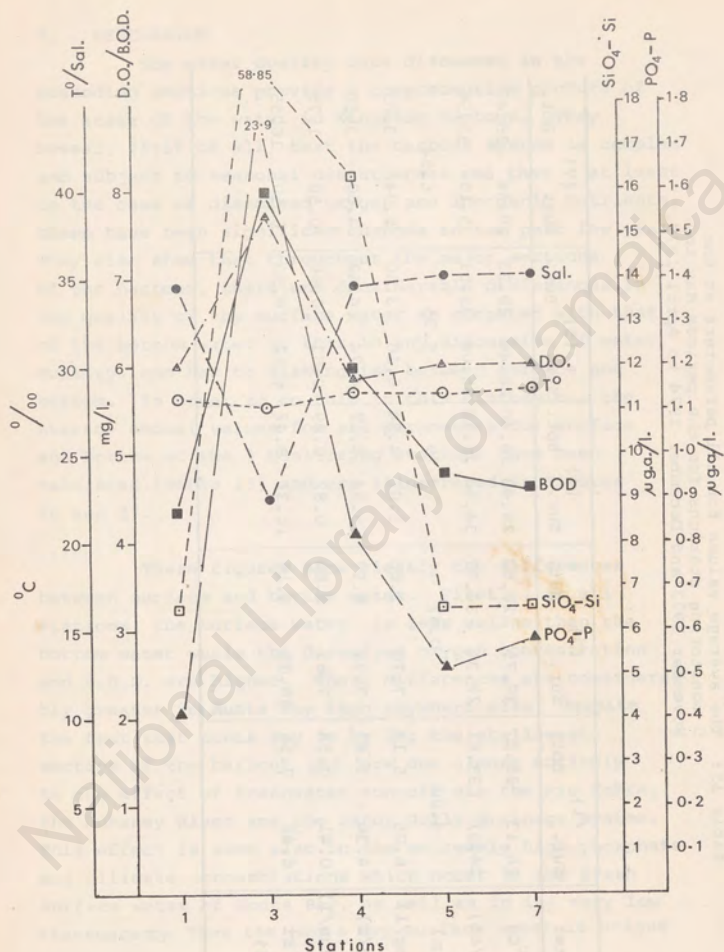


Figure 26

The average surface values for all water quality parameters at the 5 monitoring stations for the 1973 - 75 sampling period.

Table 15: The average values for all parameters at the 5 monitoring stations for the periods May to November 1973 and December 1974 to April 1975.

Parameter	(1)		(3)		(4)		(5)		(7)	
	Sur.	Bot.	Sur.	Bot.	Sur.	Bot.	Sur.	Bot.	Sur.	Bot.
Temp. (°C)	28.13	28.27	27.75	28.69	28.48	28.40	28.46	28.33	28.64	28.47
Sal. (°/oo)	34.51	35.61	22.34	34.77	34.44	35.58	35.08	35.51	35.15	35.56
Trans. (m)	4.83		0.97		3.79		5.95		6.54	
D.O. (mg/l)	6.05	5.13	7.70	3.68	5.87	4.34	6.16	3.60	5.94	3.02
BOD (mg/l)	4.36	2.67	7.94	6.57	5.94	4.17	4.74	4.42	4.60	3.50
PO ₄ -P (µg/l)	0.41	0.54	7.63	0.84	0.82	0.89	0.51	0.96	0.58	1.75
SiO ₄ - Si (µg/l)	6.48	7.36	58.85	9.16	16.31	9.42	6.52	9.90	6.50	16.55

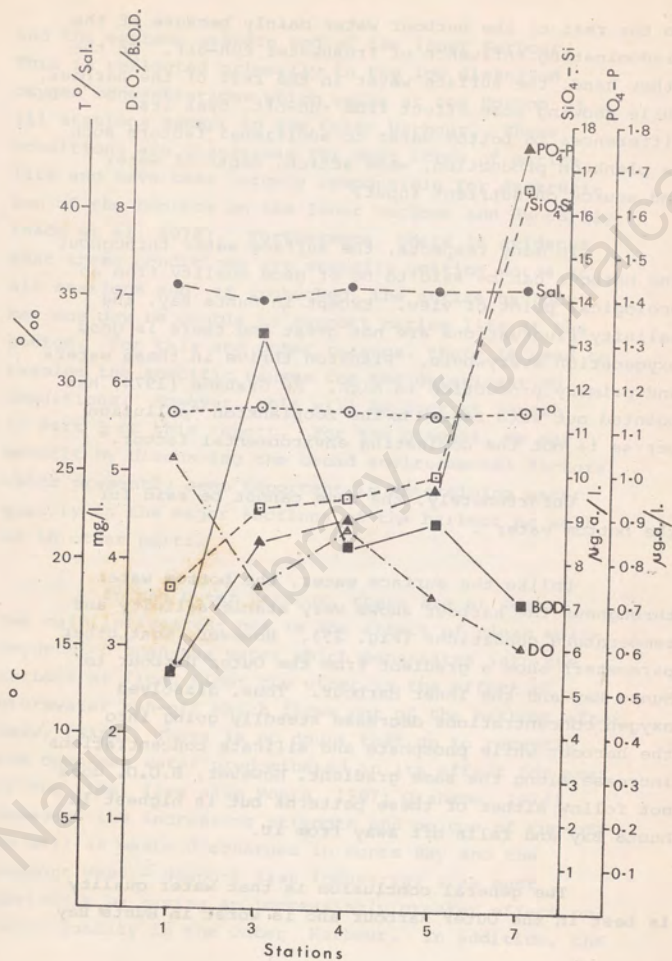


Figure 27

The average bottom values for all water quality parameters at the 5 monitoring stations for the sampling period 1973 - 75.

to the rest of the harbour water mainly because of the predominating influence of freshwater run-off. On the other hand, the surface water in the rest of the harbour, while showing some effect from run-off, owes its differences to bottom water to additional factors such as plankton production, wave action, depth of water and source of nutrient input.

In many respects, the surface water throughout the harbour can be said to be of good quality from an ecological point of view. Except in Hunts Bay, the salinity fluctuations are not great and there is good oxygenation everywhere. Plankton thrive in these waters and primary production is high. As Grahame (1974) has pointed out with regard to the zooplankton "pollution per se is not the dominating environmental factor."

Unfortunately, the same cannot be said for the bottom water .

Unlike the surface water, the bottom water throughout the harbour shows very stable salinity and temperature conditions (Fig. 25). However, most other parameters show a gradient from the Outer Harbour to Hunts Bay and the Inner Harbour. Thus, dissolved oxygen concentrations decrease steadily going into the harbour while phosphate and silicate concentrations increase along the same gradient. However, B.O.D. does not follow either of these patterns but is highest in Hunts Bay and falls off away from it.

The general conclusion is that water quality is best in the Outer Harbour and is worst in Hunts Bay

and the extreme eastern end of the Inner Harbour. This is reflected primarily in the low dissolved oxygen concentrations which exist at the bottom at all stations except in the Outer Harbour. These conditions are unsuitable for most forms of marine life and have been largely responsible for destruction of the benthos in the Inner Harbour and Hunts Bay (Wade et al, 1972). Furthermore, there is evidence that these conditions are steadily getting worse at all stations and, if unchecked, the entire harbour may one day be unable to support marine life at the bottom. For this and other reasons, there is need to examine the specific causes for the deteriorating conditions. However, this will be done at length in Part 3 of this report. For the present, we may benefit by discussing the broad environmental factors which presently seem important in determining water quality in the major sections of the harbour as well as in other parts.

In the Outer Harbour, there are at least two main influences: one is the effect of clean well-oxygenated open-sea water which penetrates into the harbour at flood tide; the other is the effect of stormwater run-off which flows out of the harbour after heavy rains. There is no doubt that up to recently the open-sea water predominated in its effect for most of the time. (See also Moore, 1967; Grahame, 1974). However, the increasing strength and volume of run-off as well as waste discharges in Hunts Bay and the Newport West - Newport East industrial area must obviously be having an increasingly greater effect on water quality in the Outer Harbour. In addition, the

opening up of Dawkins Pond to the Outer Harbour in the past five years with the resultant discharge of nutrient rich water to it (some from a municipal sewage treatment plant) must also be partly responsible for the general decline in water quality which has taken place in the Outer Harbour. In particular, the increases in nutrient concentrations and frequency of plankton blooms in that section of the Outer Harbour can be directly attributed to the Dawkins Pond discharge via the new channel.

Hunts Bay, with its low salinity, nutrient rich and high B.O.D. water already receives too much storm-water run-off and waste discharges for the maintenance of good water quality. Furthermore, since there does not seem to be any prospect for a decrease in discharges, there is no likelihood of the water quality improving. In fact, the construction of the solid-fill causeway in recent years has contributed to a worsening of water quality and will, in all likelihood, continue to do so by impoundment of waste material, reduction of wave action and increase of stagnation. However, if this happens, the effect will not be confined to Hunts Bay but will, with periodic partial flushing of the bay, extend to the Inner and Outer Harbours through discharge of poor quality water. J. Grahame (1974) and E.S. Grahame (personal communication) have identified zooplankton and phytoplankton communities which are peculiar to the estuarine environment of Hunts Bay. If present water quality trends continue and Hunts Bay water begins to exert an even greater effect on other sections of the harbour, it is possible that these plankton communities could extend further outside Hunts Bay than they presently do and eventually modify the

existing communities. If this occurs, further changes in the ecological system could then take place.

The third major section of the harbour, the Inner Harbour, is marked by fairly consistent water quality characteristics. Salinity remains high year-round both at the surface and bottom, while bottom D.O. levels are almost always low and nutrient concentrations almost always high. In fact, these conditions are most pronounced in the extreme eastern end of the harbour where, on account of the high nutrient levels, plankton production is extremely high, and contributes to oxygen deficiency in the bottom water (Grahame, 1974). However, poor oxygen conditions in this part of the harbour are also caused by rapid uptake of oxygen by the bottom deposits as well as by poor circulation and mixing at maximum depth.

The inputs of nutrients to the Inner Harbour are varied and diffuse while the origin of the bottom sediments is uncertain. Hence, it is difficult to attribute some of the factors responsible for poor water quality in this area to specific pollution sources. Nevertheless, the impact of waste discharges to the Inner Harbour cannot be discounted, especially in view of the fact that evidence indicates that water quality in this part of the harbour is deteriorating rapidly and may be due to recent factors.

A major area in the harbour of highly variable water quality characteristics is that between Hunts Bay causeway, the old Kingston Wharves and Middle Ground shoal. This area represents the

convergence of the three major sections of the harbour, namely the Outer Harbour, Hunts Bay and the Inner Harbour and hence the water quality here is subject under different conditions to the influence of these three water masses. Thus after heavy rains and run-off, the predominating effect is from Hunts Bay, while at other times under the influence of strong flood tides, Outer Harbour water and even open-sea water may penetrate far into it. Under normal conditions, however, that is with moderate tides and strong E.S.E. sea breezes, the water in this area has mostly the characteristics of the Inner Harbour water with high salinity, high nutrients, and low bottom oxygen concentrations.

The variable water quality conditions in this area are both seasonal and diurnal and are reflected to a large extent in the data for station 4. However, whereas the means of values for most parameters at this station are intermediate when compared with those for the rest of the harbour, the ranges of values are often extreme. As a result, the interpretation of overall water quality conditions in this area is more difficult and uncertain than for elsewhere. Nevertheless, certain specific comments may be made regarding the conditions in two well defined sections. One of these is the Newport West shipping basin; the other is the refinery to Kingston Wharves shoreline.

Because of its semi-enclosure and alignment with respect to the prevailing currents, the Newport West shipping basin is effectively cut off from much of the rest of the harbour, and water conditions in it therefore remain relatively stable. These conditions

however, are determined by several unfavourable factors such as the discharge of 3.5 mgd of primary treated sewage effluent and various industrial and ship wastes directly to it. As a result water quality in this basin is always very poor and appears to be getting worse.

The refinery to Kingston Wharves shoreline is marked by the discharge of several waste effluents and polluted gully streams at surface along the coast. These include 3.5 mgd of primary treated sewage, slaughter-house wastes and soap, detergents and oil wastes. Under the influence of the sea breezes during the day, these effluents back up along the shore instead of dispersing into deeper water and so produce a zone of poor quality water along the shore. This water is characterised by its high nutrient levels, poor transparency due to suspended matter and slime, oily appearance and, at times, quite noticeable odour. At night, however, under the influence of the land breezes, this water is driven away from the shore and carried south across the harbour over toward the Palisadoes. Its effect on water quality at station 4 may then be quite noticeable.

The Port Royal mangrove area represents a small subsystem of the harbour. Water quality here is influenced by its own special features as well as by inflow of water from the major sections of the harbour. For example, poor quality water arrives in the area from Hunts Bay after heavy run-off as well as from the Newport West - Newport East industrial area at nights. This water may become trapped in parts of the lagoon system where it may persist for some time (Goodbody, 1961),

or may be flushed at ebb tide depending on the currents. Where tidal circulation is good, exchange of water with the Outer Harbour normally results in removal of pollutants and replenishment of oxygen, while in those places where it is poor, the water may become foul and stagnant. However, this is influenced to a large extent by biological activity, and in certain parts of the mangroves, water quality remains fairly good despite the slow turnover of water. However, the present feeling, based on personal experience of the mangroves over the past ten years or so, is that the general conditions in the mangrove area have declined significantly, due mostly to poor quality water flowing into it from Hunts Bay and the Newport West - Newport East area.

The final section of the harbour to be considered and, in many respects, the most recent, is Dawkins Pond; for until a few years ago with the creation of the channel through the Port Henderson spit, Dawkins Pond was only connected with the rest of the harbour through Hunts Bay. Now, however, there is a direct connection with the Outer Harbour. Basically, Dawkins Pond is very similar to Hunts Bay and is characterised by heavy run-off and waste discharges resulting in low salinities, high nutrient levels, low transparency and low bottom oxygen concentrations. However, even more than Hunts Bay, Dawkins Pond has undergone rapid physical changes due to recent urban development such as mangrove destruction, deepening, finger channelling, and urban drainage. Thus the water quality in parts of Dawkins Pond has already become worse than in Hunts Bay, and it appears that this will continue and spread. Furthermore, as discussed earlier on, its effect on the Outer Harbour water is already evident and is expected to worsen as more changes take place

including the doubling or more of sewage effluent discharge to the pond.

The data discussed in detail for the five regular monitoring stations in Kingston Harbour together with the data obtained by occasional sampling in other parts present a comprehensive picture of water quality conditions in the harbour. The outstanding conclusions are that bottom oxygen conditions throughout most of the harbour are unfavourable for marine life and are getting worse. Furthermore, nutrient concentrations everywhere are high and are getting higher. How these two facts are related has been suggested in preceding discussions, but has not been elaborated on. That will be the subject of investigation in Part 3 of this report. However, on overall consideration, these and all other parameters studied point to an unmistakable trend of rapidly deteriorating conditions in Kingston Harbour. How much further this trend will continue cannot be ascertained with certainty.

Inasmuch as the determination of water quality based on bacterial levels has been outside the scope of this study, they have not been discussed in any detail. Thus the conclusions reached above pertain only to ecological parameters. However, this in no way means that bacterial levels are unimportant in the overall assessment of water quality, especially for public health purposes. Indeed, as far back as 1967 (Government of Jamaica, 1967) the importance of these levels in Kingston Harbour was stressed and the conclusion reached that from a public health point of view, the water quality in much of the harbour was substandard. The few data obtained since

then support this conclusion and indicate a general spreading of these conditions. However, it now appears high time that a thorough bacterial resurvey of Kingston Harbour be initiated.

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10. SUMMARY

(1) Temperature, salinity, transparency, dissolved oxygen, biochemical oxygen demand, nitrates + nitrites phosphates and silicates were routinely measured at monthly intervals at 5 monitoring stations in Kingston Harbour. Most parameters were measured at 5 metre depth intervals. In addition, more than 50 stations around the periphery of the harbour were sampled occasionally.

(2) Horizontal and vertical temperature differences in the harbour are generally less than 1°C and are insignificant. The annual range is 3.5°C ($26.3 - 29.7^{\circ}\text{C}$) with July and August being the warmest months and January to March being the coolest.

(3) The salinity of bottom water in Kingston Harbour remains constant year-round (35.6 ‰). However, the surface water, especially in the top one metre, is subject to various degrees of dilution after heavy rains. This is greatest in Hunts Bay where the salinity may fall to less than 1 ‰ on occasions. However, surface salinity at the other stations seldom falls below 30 ‰ after rains and may recover to normal levels within a few weeks.

(4) The poorest transparency is in Hunts Bay where run-off is greatest, and is at the worst during the rainy months. Average transparency in Hunts Bay is only 0.97 m compared with 3.79 m to 6.54 m in the rest of the harbour.

(5) The dissolved oxygen concentration in the surface water throughout the harbour is high. However, except for the Outer Harbour, all other parts

of the harbour have oxygen deficiency at the bottom.

(6) The dissolved oxygen concentrations at all depths below the surface decline as one moves up the harbour. However, this decline is greatest between the Outer and Inner Harbours and in the Upper Basin.

(7) Bottom oxygen conditions in the Inner Harbour also deteriorate with depth and the worst conditions occur at the extreme eastern end of the Inner Harbour where the average saturation level is less than 50%.

(8) Bottom oxygen conditions throughout the harbour have been deteriorating over the past 5 years. However, this deterioration is greatest in Hunts Bay and the Outer Harbour.

(9) The biochemical oxygen demand is greatest in Hunts Bay (7.25 mg/l average) and lowest in the Outer Harbour (3.51 mg/l), and the highest B.O.D.'s occur in the surface water during the rainy months. The high B.O.D. values in the harbour contrast with the lower value of 2.0 mg/l obtained for the open sea near Lime Cay.

(10) Inorganic nutrients in the form of nitrates + nitrites, phosphates and silicates have very high concentrations in Kingston Harbour. The highest concentrations are in Hunts Bay, followed by the Inner Harbour and the Outer Harbour. All the nutrients show a seasonal distribution related to the rainfall pattern.

(11) All parts of the harbour show significant vertical differences in nutrient concentrations. In Hunts Bay the surface water has higher concentrations than the bottom water. In most of the rest of the harbour, however, the bottom water normally has higher concentrations than the surface water.

(12) Higher surface concentrations in Hunts Bay are attributed to surface run-off and waste discharges while higher bottom concentrations in the rest of the harbour are due to benthic recycling and possibly submarine drainage in the Upper Basin.

(13) Since the first nutrient survey was conducted in 1962 - 64, all the nutrients have shown an overall increase in concentrations. The greatest increase has been with the phosphates, followed by nitrates + nitrites and the silicates.

(14) The Outer Harbour has shown a greater increase in nutrients since 1962 - 64 than the Inner Harbour.

(15) The increase in nutrients cannot be attributed to greater freshwater run-off. However, waste discharges have increased considerably since 1962 - 64 and is likely to be the main factor responsible for the increases, especially in the Outer Harbour.

(16) The increasing frequency of plankton blooms in all parts of the harbour may be linked to the increase in nutrient concentrations. However, the precise factors which trigger plankton blooms in Kingston Harbour are still not understood.

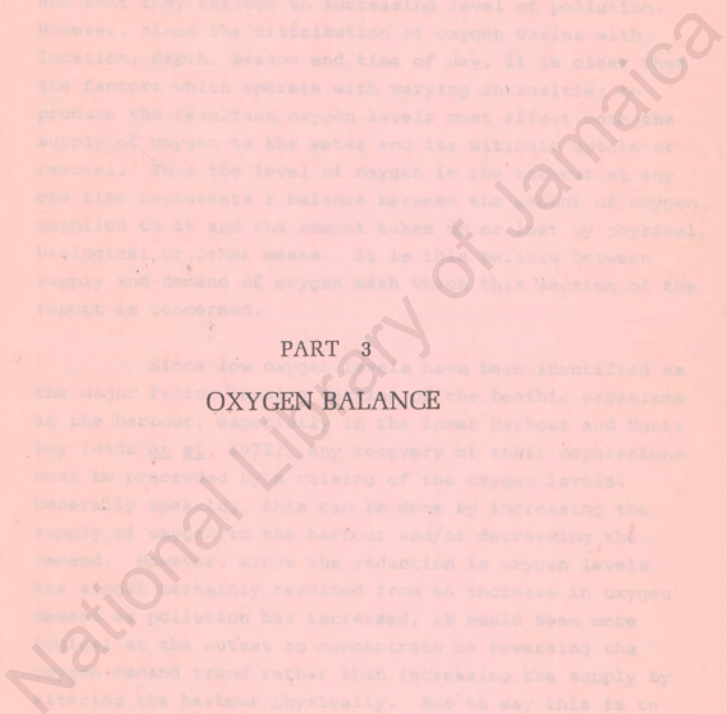
1. INTRODUCTION

The water quality data discussed in Part 2 of this report clearly show that deficient oxygen levels exist throughout most of the bottom water of the harbour and that they reflect an increasing level of pollution. However, since the distribution of oxygen varies with location, depth, season and time of day, it is clear that the factors which operate with varying intensities to produce the resultant oxygen levels must affect both the supply of oxygen to the water and its utilization or removal. Thus the level of oxygen in the water at any one time represents a balance between the amount of oxygen supplied to it and the amount taken up or lost by physical, biological or other means. It is the balance between supply and demand of oxygen with which this section of the report is concerned.

PART 3

OXYGEN BALANCE

Since low oxygen levels have been identified as the major factor limiting the benthic organisms in the harbour, especially in the Inner Harbour and Bights by loads of 21. 1972, any recovery of their populations must be preceded by a raising of the oxygen levels. Generally speaking, this can be done by increasing the supply of oxygen to the harbour and/or decreasing the demand. However, where the reduction in oxygen levels has not certainly resulted from an increase in oxygen demand, as at the outlet to concentrate on reversing the demand trend rather than increasing the supply by filtering the harbour physically. But to say this is to speculate for so far we have not yet examined those factors which utilize the oxygen of the harbour nor those which supply it, and this is necessary if we wish to



(17) Kingston Harbour exhibits all the typical characteristics of a eutrophic water body. Thus, whereas the surface waters support large plankton populations, the bottom waters have poor benthic populations.

(18) Overall water quality in Kingston Harbour is worst in Hunts Bay and the Upper Basin and is best in the Outer Harbour. However, deterioration is taking place more rapidly in the Outer Harbour than anywhere else.

(19) Certain discrete sections of the harbour have water quality conditions which are worse than in the open harbour. Some of these areas are Dawkins Pond, the Newport West shipping basin and the refinery to Kingston wharves shoreline.

(20) All the evidence on water quality in Kingston Harbour point to an unmistakable trend of rapidly deteriorating conditions. How much further this trend will continue cannot be ascertained with certainty.

1. INTRODUCTION

The water quality data discussed in Part 2 of this report clearly show that deficient oxygen levels exist throughout most of the bottom water of the harbour and that they reflect an increasing level of pollution. However, since the distribution of oxygen varies with location, depth, season and time of day, it is clear that the factors which operate with varying intensities to produce the resultant oxygen levels must affect both the supply of oxygen to the water and its ultimate uptake or removal. Thus the level of oxygen in the harbour at any one time represents a balance between the amount of oxygen supplied to it and the amount taken up or lost by physical, biological or other means. It is this balance between supply and demand of oxygen with which this section of the report is concerned.

Since low oxygen levels have been identified as the major factor causing decline of the benthic organisms in the harbour, especially in the Inner Harbour and Hunts Bay (Wade et al., 1972), any recovery of their populations must be preceded by a raising of the oxygen levels. Generally speaking, this can be done by increasing the supply of oxygen to the harbour and/or decreasing the demand. However, since the reduction in oxygen levels has almost certainly resulted from an increase in oxygen demand as pollution has increased, it would seem more logical at the outset to concentrate on reversing the oxygen demand trend rather than increasing the supply by altering the harbour physically. But to say this is to speculate for so far we have not yet examined those factors which utilise the oxygen of the harbour nor those which supply it, and this is necessary if we wish to

arrive at sound conclusions. In other words, as far as possible, we need to be able to quantify the contribution from all the various sources to the supply and demand budget so as to assess those which are most critical and capable of change. Only then can a feasible program for improving the oxygen conditions be worked out.

Unfortunately, the study reported here has not gone far enough in investigating all the critical factors and hence the supply and demand budget cannot yet be drawn up with accuracy. Nevertheless, sufficient has been done to indicate what the important factors might be and what further investigations are necessary to complete the picture. Moreover, this study also points to the nature and enormity of the task that lies ahead in improving the oxygen balance, whether it be by increasing the oxygen supply or by reducing the demand. For these reasons, the information presented in this section of the report, although incomplete, is of importance.

2. OXYGEN DISTRIBUTION AND SUPPLY

The distribution of oxygen in the sub-surface waters of the harbour shows a definite pattern of higher concentrations nearer the open sea and lower concentrations in the inner parts (Fig. 16). Thus the Outer Harbour has the best oxygen conditions while Hunts Bay and the Inner Harbour, especially the Upper Basin, have the worst. However, the gradient of oxygen levels is not gradual throughout the harbour but changes rapidly in three areas. These are (a) the area of the narrow ship channel connecting the Outer Harbour with the Inner Harbour; (b) the area of the causeway across the mouth of Hunts Bay; and (c) the area where the deep Upper Basin slopes off from the rest of the Inner Harbour. These three areas are marked by sudden changes in topography and depth and represent obvious boundaries to the different sections of the harbour. Thus, to some extent, each section of the harbour may be considered as a discrete water basin with its own characteristic hydrography and water quality. However, this does not mean that each is a closed system with no exchange of water with the others, for we know that there is, but it does indicate that within each there may be local factors peculiar to that area which help to determine its water conditions. Indeed, the water quality data presented in Part 2 provide evidence that this is so especially in the bottom waters where the water quality is markedly different. Thus, it would be useful in assessing the oxygen budget of the entire harbour to consider each of these areas separately and to compare them with the open sea outside of Port Royal where water quality is good and there is no oxygen depletion.

In the open sea near to Lime Cay, both surface and bottom waters are almost always saturated with oxygen and there is no marked seasonal fluctuation as within the harbour. Plankton blooms or red tides seldom if ever occur in this area and only under very exceptional circumstances such as extreme flood rains (Goreau, 1964) does stormwater run-off affect the water.

In the Outer Harbour, however, although the average oxygen conditions are good, the water is not free from the effect of plankton blooms and stormwater, and periodic fluctuations occur. Furthermore, not all parts of the Outer Harbour enjoy the same oxygen conditions as there is a steady decline towards the ship channel and deep semi-isolated basins like Hulk Hole show appreciably lower concentrations. Consequently, the Outer Harbour has a lower oxygen budget than the open sea and is subject to variations.

There is a dramatic fall-off in oxygen levels between the Outer Harbour and the Inner Harbour in the region of the ship channel (see Fig. 16). Since this narrow channel is the only deep connection between these two arms of the harbour and its depth is less than the average depth of either basin, it means that there can be no direct communication between the bottom water of these two arms of the harbour. Goodbody (1970) has therefore likened the Inner Harbour to a partially closed system in which exchange of water with the Outer Harbour is only in the narrow confines of the ship channel and over the shallow depths of the Middle Ground Shoals. Thus, the flow of tidal water into the Inner Harbour is limited largely to the surface, and bottom water can only be

replaced by first rising towards the surface in a vertical circulation. Since this vertical circulation is generated by wind, however, the replacement of bottom water within the Inner Harbour is subject to seasonal fluctuations and, for long periods during the calm months, it may be very marginal. Hence, circulation of water in the Inner Harbour resulting in the flushing and replacement of bottom water may be very critical. On the other hand, there is no problem with the surface water.

The Upper Basin, having a greater depth than the rest of the Inner Harbour, has an exaggerated vertical circulation problem. As a result, there is even less turnover of the bottom water and hence a greater oxygen deficiency problem at the bottom.

In Hunts Bay, circulation has been reduced by construction of the solid-fill causeway. Hence, there is much slower turnover of water inside the causeway than before and oxygen concentrations have fallen. One effect of this is a sharp decline in oxygen concentrations across the causeway.

It is clear from the above that the amount of circulation in each section of the harbour helps to determine its oxygen condition. Unfortunately we do not have data available to accurately determine the level of circulation throughout the harbour but, based largely on theoretical considerations we can attempt some rough estimates. To do this, it is necessary to make certain assumptions about tidal circulation in the harbour although some of these conditions may not apply for all or most of the time. Nevertheless, by so doing, any errors that may

be made tend to produce an overestimation of tidal circulation and hence should not exaggerate the oxygen supply problem in Kingston Harbour. The necessity for this will become obvious as we proceed.

We will assume that tidal amplitudes throughout Kingston Harbour are equal and that the currents consist of simple flood and ebb tide movements in roughly opposite directions. Furthermore, there is no difference between surface and bottom currents and there is uniform flow across each cross section. All tidal water entering the harbour does so through the channel between Port Royal and Port Henderson and all of this water is saturated with oxygen at 6.2 mg/l. (Govt. of Jamaica, 1968). This represents approximately the best tidal condition that may exist for a semi-enclosed elongated bay like Kingston Harbour.

In such a case, new water is brought into the harbour on each flood tide and thus provides a fresh supply of oxygen. The volume of water which enters on each tidal cycle is the tidal prism (obtained by multiplying area of harbour by tidal amplitude) and the amount of oxygen supplied is this volume times the concentration. Since all of the flood tide flow enters through the Outer Harbour, all of the oxygen contained in it is theoretically available to this section of the harbour for oxygenation. However, in the Inner Harbour and Hunts Bay where the tidal prisms are only a part of the total for the harbour (74% and 8% respectively), the supply of new water must at the most be proportional. Furthermore, the water which enters the Inner Harbour and Hunts Bay has already lost some oxygen to the Outer Harbour, and its

concentration can be expected to be no higher than the average concentration in the Outer Harbour (5.6 mg/l). Thus, the supply of oxygen to these parts cannot be greater than 66.8% and 7.2% of that to the Outer Harbour. Similarly in the Upper Basin where the tidal prism is 14% of the total for the harbour, the possible supply of oxygen is only 9.4% of that in the Outer Harbour (the oxygen concentration of incoming water has fallen to an average of 4.7 mg/l by the time it reaches the Upper Basin). From these straightforward considerations, it can be seen that the supply of oxygen to the Outer Harbour by tidal circulation is at least ten times that in the Upper Basin and at least thirteen times that of Hunts Bay.

However, under more likely conditions of tidal flow in which surface currents are stronger than bottom currents and the oxygen is not distributed evenly throughout the water column, the oxygen supply to the surface by tidal flow is almost certainly greater than that to the bottom, especially in the Inner Harbour. Thus, the oxygenation in the bottom water of the Upper Basin is likely to be considerably less in relation to the Outer Harbour than the 9.4% estimated above. Furthermore, the situation is also affected by the strong E.S.E. and S.E. sea breezes which blow up the harbour in opposition to flood tide flows and probably reduce the tidal prism in the Inner Harbour during the windy months. Add to this the problem of exchange of bottom water between the Outer and Inner Harbours due to the Middle Ground Shoal and it can be readily appreciated that the actual oxygen supply to the Upper Basin by tidal flow is quite likely to be considerably less than that estimated above.

With regard to Hunts Bay, the actual conditions are quite different from the idealised situation due to the causeway restricting tidal flow. Thus the tidal prism has probably been reduced by reduction of the amplitude and there is less circulation than before. The oxygen supply by flood tide flow is consequently less than the estimate made although we cannot say by how much until more data are available.

Whereas oxygen supply by tidal flow to various parts of the harbour varies with location, oxygen supply by wind and wave action is probably much the same throughout the harbour since all parts (with the exception of Hunts Bay) have approximately similar conditions. However, the variation with time is much greater than for tidal flow and is important.

The percentage frequency of all winds in Kingston Harbour is as follows (Govt. of Jamaica, 1968):

< 4 knots	27.0%
4 - 10 "	44.0%
10 - 21 "	25.6%
21 - 33 "	3.2%
> 33 "	0.2%

Since the rate of exchange of gases across the air - sea interface increases approximately as the square of the velocity (Kanwisher, 1963), the wind speed frequencies for Kingston Harbour would result in oxygen transfer from air to sea according to the following percentage volumes:

< 4 knots	2.0%
4 - 10 "	22.5%
10 - 21 "	57.7%
21 - 33 "	17.6%

Thus winds between 10 and 21 knots in strength are responsible for the overwhelming amount of oxygen that enters Kingston Harbour by diffusion from the air (57.7%) while winds below 4 knots result in very little (2.0%).

It follows that during those days when the average wind-speed is 4 knots or less, the oxygen supply by diffusion may be only 3.6% of that when winds between 10 - 21 knots blow throughout the day. Hence, there may be a difference in supply of nearly 30 times between calm and windy days. This difference may be largely responsible for the occurrence of either anoxic conditions in the bottom water in the Upper Basin or saturated oxygen conditions as shown in Figure 11. However, the amount of vertical mixing is also important, but as this also increases with wind speed and wave action it is impossible to separate its effect from that of diffusion alone.

The remaining sources of oxygen supply to Kingston Harbour are the phytoplankton and benthic plants which give off oxygen in the day during photosynthesis. We have seen that during plankton blooms, the concentration of oxygen in the surface water may increase significantly and that immediately above turtle grass beds supersaturation frequently occurs. However, it has not been possible to measure the contribution by these sources to oxygen in the harbour and hence their role in the oxygen budget cannot be quantified.

3. OXYGEN DEMAND

The demand for oxygen in any system like Kingston Harbour is exerted by a number of factors occurring in the water and on the bottom. It is the total of their oxygen demands at any one time which determines how much of the oxygen supplied to the system is used up and hence how much remains in solution in the water. The factors which exert this oxygen demand are therefore discussed below.

3.1 The Water

The pattern of oxygen demand by the water as described in Part 2 of this report is clear. The highest B.C.D's occur in Hunts Bay (avg. 7.25 mg/l) and the lowest in the Outer Harbour (avg. 3.51 mg/l). The B.O.D's in the Inner Harbour are intermediate and show a definite decline towards the Upper Basin (5.05 - 4.05 mg/l). Generally, the surface water exerts a higher oxygen demand than the bottom water and the greatest demand is exerted during the rainy months. The high average B.O.D's of Kingston Harbour contrast with the lower value of 2.0 mg/l. for the open sea near Lime Cay. Furthermore, the harbour water exerts periodic excessive demands during plankton blooms and after flood rains which the open-sea water never does.

Within the water column in Kingston Harbour a number of factors may be responsible for the high B.O.D's. Some of these are dissolved organics, suspended solids including detritus, and plankton. In order to determine the relative contribution by each of these to the total oxygen demand exerted by the water, a number of experiments was performed using water obtained from each of the main sections of the harbour.

Firstly, samples were obtained during fairly normal conditions (B.O.D. 2.3 - 7.8 mg/l) and portions filtered through either Whatman no. 1 filter paper or a sintered glass crucible. The B.O.D.₅ of both filtered and unfiltered portions were then determined in order to measure the reduction in oxygen demand due to the removal of all particulates. The results shown in Table 16 reveal that under these conditions, filtering the water and therefore removing the particulates caused an average reduction of only 13.5% in the B.O.D.₅ (or, for a few samples, 20.0% in the ultimate B.O.D.). Hence, we may conclude that under normal water conditions throughout the harbour, particulate matter in the water does not account for the high B.O.D. levels. This must therefore be due largely (at least 80%) to soluble organics.

However, the data in Table 16 also reveal that the reduction in B.O.D.₅ caused by filtering out the particulates was highest in Hunts Bay (17.1% and 19.2%) where turbidity is greatest, thus suggesting that there may be some connection either directly or indirectly between B.O.D. and suspended solids. In order to test this, a plot of mean B.O.D. against mean suspended solids for each of the 5 monitoring stations was made. The result shown in Figure 28a further suggests a correlation between the two. Finally, a plot was made of B.O.D. against suspended solids for more than forty samples throughout the harbour (Fig. 28b). The results in this case show that whereas there is generally much scatter between B.O.D. and suspended solids in the lower ranges (B.O.D. less than 5.5 mg/l), the relationship is much better at the higher levels.

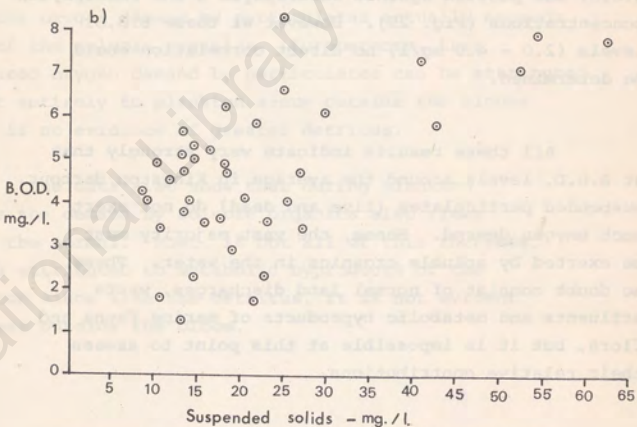
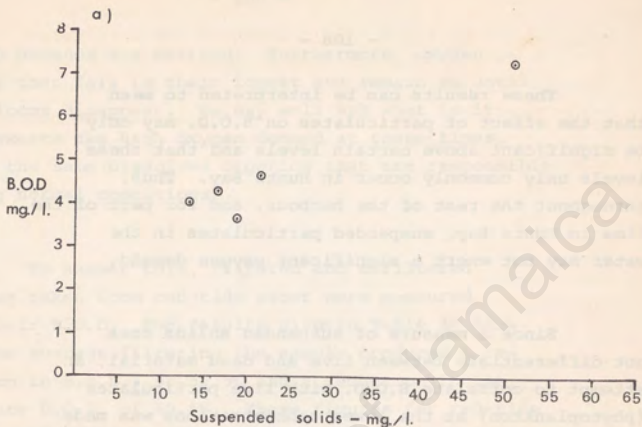


Figure 28

- a) A plot of mean B.O.D. values against mean suspended solids values for each of the 5 main monitoring stations in Kingston Harbour.
- b) A plot of individual B.O.D. values against suspended solids values for 38 samples throughout Kingston Harbour.

Table 16: The B.O.D.₅ values (mg/l) for unfiltered and filtered harbour water.

Sample	Unfiltered	Filtered	Reduction
Outer Harbour	2.3 mg/l	2.0 mg/l	13.0%
Hunts Bay	7.0	5.8	17.1
Hunts Bay	7.8	6.3	19.2
Inner Harbour	6.0	5.8	3.3
Inner Harbour	2.8	2.4	14.3
Inner Harbour	<u>5.5</u>	<u>4.8</u>	<u>12.7</u>
Average	5.2	4.5	13.5

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These results can be interpreted to mean that the effect of particulates on B.O.D. may only be significant above certain levels and that these levels only commonly occur in Hunts Bay. Thus, throughout the rest of the harbour, and for part of the time in Hunts Bay, suspended particulates in the water may not exert a significant oxygen demand.

Since a measure of suspended solids does not differentiate between live and dead material, an attempt to correlate B.O.D. with live particulates (phytoplankton) at the lower concentrations was made using data supplied by Drs. J. & E.S. Grahame . B.O.D. was plotted against Chlorophyll a and Phaeophytin concentrations (Fig. 29). However at these B.O.D. levels (2.0 - 4.0 mg/l) no direct correlation could be determined.

All these results indicate very strongly that at B.O.D. levels around the average in Kingston Harbour, suspended particulates (live and dead) do not exert much oxygen demand. Hence, the vast majority must be exerted by soluble organics in the water. These no doubt consist of normal land discharges, waste effluents and metabolic byproducts of marine fauna and flora, but it is impossible at this point to assess their relative contributions.

As reported earlier, the B.O.D. may increase to several times the average value during plankton blooms and indeed it is at such times that the maximum

oxygen demands are exerted. Furthermore, oxygen levels then fall to their lowest and remain so until the blooms disappear. We may well ask what is it that exerts the high oxygen demand at these times. Is it the same dissolved organics that are responsible during normal conditions?

To answer this, filtered and unfiltered samples taken from red-tide water were measured for their B.O.D. The results given in Table 17 show that on average filtering the sample produced a reduction in B.O.D.₅ of 52.5% and a reduction in the ultimate B.O.D. of 59.5%. These figures for red-tide water are appreciably higher than those obtained under normal water conditions and show that unlike then the oxygen demand by particulates actually exceeds that of the soluble organics. Furthermore, this increased oxygen demand by particulates can be attributed almost entirely to plankton since outside the blooms there is no evidence of greater detritus.

The data also show that during plankton blooms the demand by soluble organics also rises above the normal. Most, if not all of this increase, can be attributed to metabolic byproducts of the plankton since like the detritus, it is not evident in areas outside the bloom.

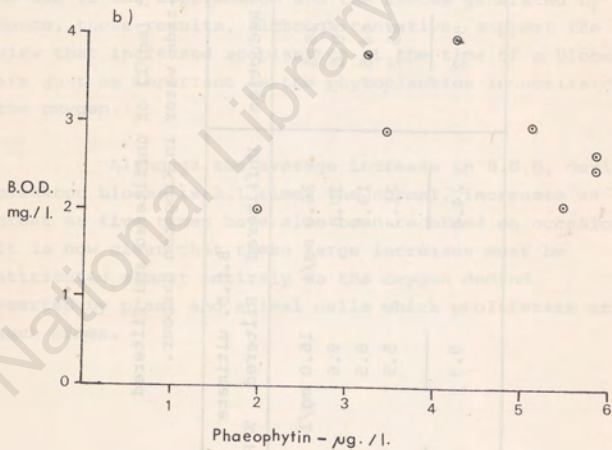
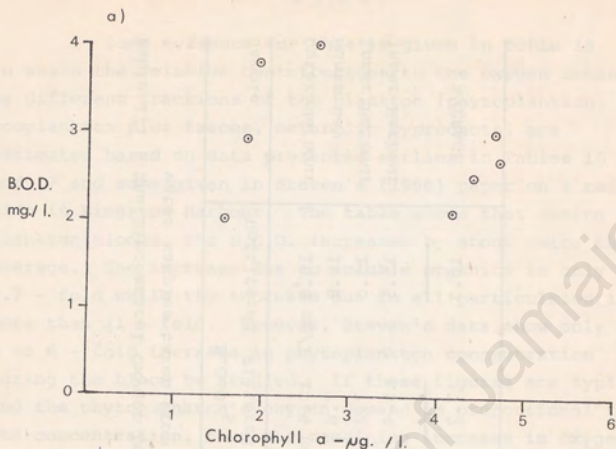


Figure 29

Plots of B.O.D. values in Kingston Harbour
against Chlorophyll a and Phaeophytin
concentrations.

Hence, it is safe to conclude that the greater oxygen demand during a plankton bloom is exerted primarily by the particulates (live and inert) and only secondarily by metabolic byproducts. Other soluble organics appear to exert no more demand than at other times.

No attempt was made to differentiate experimentally between the oxygen demand exerted by phytoplankton and zooplankton during a bloom in Kingston Harbour. However, Grahame (1974) has shown that the increase in phytoplankton populations during one bloom he studied was closely paralleled by a similar increase in the zooplankton. Also Seki et al (1974) have demonstrated that during a red tide in Tokyo Bay, the contribution to oxygen consumption by the zooplankton was significant due to its grazing activity resulting in increased phytoplankton growth and the rapid transportation and sedimentation of organic material from the surface to the bottom. The latter was further mainly responsible for the formation of an anoxic layer in the bottom water since phytoplankton was absent at this depth. Hence the contribution of zooplankton to oxygen consumption could possibly be just as important as the phytoplankton during blooms in the harbour.

Table 17: The Biochemical Oxygen Demand (mg/l) of unfiltered and filtered water samples taken from red-tide water in Kingston Harbour.

Sample	B.O.D. ₅			B.O.D. ultimate		
	Unfiltered	Filtered	% Reduction	Unfiltered	Filtered	% Reduction
Outer Harbour	16.9 mg/l	10.4 mg/l	38.5	26.0 mg/l	16.0 mg/l	38.5
Hunts Bay	19.8	7.8	60.6	30.8	9.6	68.8
Inner Harbour	13.0	7.2	44.6	19.5	8.5	56.4
Inner Harbour	15.5	5.4	65.2	21.3	5.5	74.2
AVERAGE	16.3	7.7	52.2	24.4	9.9	59.5

Some evidence for this is given in Table 18 in which the relative contributions to the oxygen demand by different fractions of the plankton (phytoplankton, zooplankton plus faeces, metabolic byproducts) are estimated based on data presented earlier in Tables 16 and 17 and some given in Steven's (1966) paper on a red tide in Kingston Harbour. The table shows that during plankton blooms, the B.O.D. increases by about twice the average. The increase due to soluble organics is only 0.7 - fold while the increase due to all particulates is more than 11 - fold. However, Steven's data show only a 4 to 6 - fold increase in phytoplankton concentration during the bloom he studied. If these figures are typical and the phytoplankton's oxygen demand is proportional to its concentration, then the remaining increase in oxygen demand exerted by all particulates (5 to 7 - fold) must be due to the zooplankton and the faeces generated by it. Hence, these results, although tentative, support the view that increased zooplankton at the time of a bloom are just as important as the phytoplankton in utilising the oxygen.

Although the average increase in B.O.D. during plankton blooms is 2.1 times the normal, increases as great as five times have also been recorded on occasions. It is now clear that these large increases must be attributed almost entirely to the oxygen demand exerted by plant and animal cells which proliferate at such times.

Table 18: A comparison of Phytoplankton concentration and B.O.D. (mg/l) in Kingston Harbour during normal conditions and plankton blooms. (Phytoplankton data from Steven, 1966)

	Normal	Blooms	Increase
Phytoplankton (cells/m ³)	1120x10 ⁶	7830x10 ⁶	x 6.0
Chlorophyll a (mg/m ³)	2.57	13.70	x 4.3
B.O.D. (total)	5.2	16.3	x 2.1
B.O.D. (soluble)	4.5	7.7	x 0.7
B.O.D. (particulates)	0.7	8.6	x11.3
B.O.D. (Phytoplankton)			approx. x 4 - 6
B.O.D. (Zooplankton & faeces)			approx. x 5 - 7

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3.2 The Bottom Sediments

The biochemical oxygen demand of bottom sediments in Kingston Harbour was measured in a number of ways. Firstly, 5 cc. of freshly collected sediment taken by a small van Veen grab was placed along with water of a predetermined B.O.D. in a Hach manometer sample bottle and the B.O.D. of the water plus sediment measured. Knowing the B.O.D. of the water alone, that of the sediment was obtained by difference. The water and sediment mixture was vigorously stirred throughout the determination.

The results are given in Table 19 with the B.O.D.'s expressed as milligrams oxygen per litre of sediment. This measure gives a good comparison of the oxygen demand by the sediments from different parts of the harbour and shows not unexpectedly that the Hunts Bay sediments exert the highest demand. Moreover, the decline in B.O.D. of the sediments outside of Hunts Bay is very similar to that of the water with a general reduction up the Inner Harbour and towards the Outer Harbour. However, this measure does not indicate how much oxygen might actually be consumed in the field since it is related to the volume of resuspended material and there is no method of equating this with actual conditions.

In order to overcome this problem, a second measure of benthic oxygen demand was devised, in this case related to area of bottom sediment. In the first of these experiments, sediment samples were allowed to settle in the Hach manometer sample bottles to produce varying thicknesses of sediment (1, 2, 4, 8 cm) , uniformly covering the bottom of the bottle (35 cm² area) .

Table 19: The 5-day B.O.D. of sediments in Kingston Harbour measured as milligrams oxygen per litre of sediment.

Sample	B.O.D. ₅
Outer Harbour (Station 1)	3017 mg/l
Hunts Bay (Station 3)	9717
Inner Harbour (Station 4)	4717
Inner Harbour (Station 5)	3417
Inner Harbour (Station 7)	3417

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With careful addition of water of a predetermined B.O.D. and without stirring, the B.O.D. of the water plus sediment was determined. The results for one station given below show that without stirring there was no significant increase in B.O.D. with thickness of the sediment:

1 cm	4,943 mg/m ²
2 cm	4,743
4 cm	4,057
8 cm	<u>5,685</u>
Avg.	4,856

Hence, most if not all of the oxygen demand was exerted in the top 1 cm. However, since there is evidence that the bottom sediments in Kingston Harbour are not undisturbed, but show a worked area of approximately 1 cm. thickness depending on currents and wave action, it was thought that the B.O.D. per square metre of stirred sediment 1cm. thick would produce results closer to actual field conditions. Hence, further experiments were performed measuring the B.O.D. of stirred sediments 1 cm. thick from each of the 5 monitoring stations in the harbour and outside near Lime Cay and expressing the results in milligrams of oxygen per square metre of stirred sediment. These results are given in Table 20 along with the corresponding figures for unstirred samples.

The pattern of results can be seen to be consistent with other measures. What, however, is striking is the difference in oxygen demand between the stirred and unstirred samples, in the case of Hunts Bay

Table 20: The 5-day B.O.D. of stirred and unstirred sediment samples 1 cm. thick from Kingston Harbour and outside expressed as milligrams oxygen per square metre (mg/m^2)

	Stirred	Unstirred	Difference
Outer Harbour (Station 1)	20,454 mg/m^2	2,968 mg/m^2	x 6.9
Hunts Bay (Station 3)	57,543	5,228	x 11.0
Inner Harbour (Station 4)	33,284	3,425	x 9.7
Inner Harbour (Station 5)	24,854	3,653	x 6.8
Inner Harbour (Station 7)	22,968	3,653	x 6.3
Open Sea	12,273	2,503	x 4.5

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by as much as eleven times. This indicates clearly, that under different current and sea conditions, there may be large differences in the oxygen demand exerted by the bottom sediments.

Based on the measured oxygen demands of the water and sediment, it is possible to determine the total oxygen demand per unit area in each section of the harbour as follows:

Total B.O.D. per unit area equals the B.O.D. of the sediment per unit area plus the B.O.D. of all the volume of water above that area of sediment.

Thus, for example, for station 1 in the Outer Harbour the total B.O.D. per square centimetre is calculated as follows:

- (i) B.O.D. sediment = 2.0 mg/cm^2
- (ii) B.O.D. water = $3.51 \text{ mg/l} \times 1.3 \text{ l} =$
 4.6 mg/cm^2
- (iii) Total B.O.D. = 6.6 mg/cm^2

This value is based on an average B.O.D. of the water at station 1 of 3.51 mg/l and a depth of 13 metres; The B.O.D. of the sediment is that measured in the stirred condition. However, two other values are also calculated for different conditions:

- a) A minimum value using the average B.O.D. of the water and that of the unstirred sediment; and
- b) A maximum value using the B.O.D. of red-tide water (avg. 16.3 mg/l) and the stirred sediment.

Table 21: The normal, minimum and maximum B.O.D. of water and sediment per square centimetre for the 5 monitoring stations in Kingston Harbour and for the open sea near Lime Cay.

	Normal (1)	Minimum (2)	Maximum (3)
Outer Harbour (Station 1)	6.6 mg/cm ²	4.9 mg/cm ²	23.2 mg/cm ²
Hunts Bay (Station 3)	7.9	2.7	10.6
Inner Harbour (Station 4)	9.4	6.4	22.8
Inner Harbour (Station 5)	9.4	7.2	26.9
Inner Harbour (Station 7)	9.6	7.7	31.6
Open Sea	3.8	2.9	3.8

(1) Normal = B.O.D. normal water + stirred sediment
1 cm. thick.

(2) Minimum = B.O.D. normal water + unstirred sediment
1 cm. thick.

(3) Maximum = B.O.D. red-tide water + stirred sediment
(except for open sea which does not
experience plankton blooms).

The results of these calculations for each of the 5 monitoring stations within the harbour and for the open sea near Lime Cay are given in Table 21. For each station, the average B.O.D. of the water used is based on the data presented in Table 8.

The calculations (Appendix 1) reveal that except for Hunts Bay, the oxygen demand exerted by the water under normal conditions is on the average 2.5 times that exerted by the sediment. In Hunts Bay, however, the oxygen demand exerted by the sediment is 2.65 times that exerted by the water. On the other hand, during plankton blooms, the B.O.D. exerted by the water outside Hunts Bay increases to 9.76 times that exerted by the sediments while in Hunts Bay, the B.O.D. of the water rises to 0.85 that of the sediment.

The conclusion to be drawn from these figures is that under normal conditions outside of Hunts Bay and under all conditions in Hunts Bay, the sediments exert a proportionately significant oxygen demand.

Finally, the results in Table 21 show that under normal conditions, the total oxygen demand of station 7 in the Inner Harbour (Upper Basin) where the greatest demand is exerted is 2.5 times that in the open sea near Lime Cay. However, during plankton blooms, this may rise to 8.3 times.

4. OXYGEN BUDGET

Having considered how oxygen is supplied throughout Kingston Harbour and what the demand for oxygen is, we can now attempt an assessment of the supply versus demand budget. In doing so, we shall deal with each section of the harbour separately.

We have seen that under normal conditions, the Outer Harbour near its entrance is nearly always saturated with oxygen or just undersaturated. For purposes of discussion, we will assume saturation as the norm. Hence, the oxygen demand (6.6 mg/cm^2) is regularly satisfied by the supply. If we assume that each tidal cycle completely replaces the water at Station 1 in the Outer Harbour with clean open-sea water, then the supply by flood tide would be a multiple of the oxygen concentration of the new water and its volume. Therefore for each square centimetre of Outer Harbour, this is:

$$6.2 \text{ mg/l} \times 1.3 \text{ l} = 8.06 \text{ mg/O}_2/\text{cm}^2$$

which, in fact, is in excess of the demand.

The assumptions of normally saturated water and complete tidal replacement in the Outer Harbour may be slightly generous, but these are made so as to provide a suitable reference for comparison with the Inner Harbour and Hunts Bay. If anything, these assumptions will lead to a more favourable oxygen budget in these parts and thus will not make the problem of oxygen deficiency seem worse than it really is.

Earlier in the discussion on oxygen supply, we concluded that the Upper Basin section of the Inner

Harbour (Station 7) received no more than 9.4% per unit area of the supply of the Outer Harbour on each flood tide. Thus, 9.4% of 8.06 mg/cm^2 would yield a tidal supply of only $0.76 \text{ mg O}_2/\text{cm}^2$. Similarly for Hunts Bay, the supply would only be 7.2% of 8.06 mg/cm^2 which is $0.58 \text{ mg O}_2/\text{cm}^2$. Both of these figures are far short of the estimated oxygen demands exerted in these areas and leave deficits as follows:

$$\text{Upper Basin: } 9.6 - 0.76 = 8.84 \text{ mg O}_2/\text{cm}^2$$

$$\text{Hunts Bay : } 7.9 - 0.58 = 7.32 \text{ mg O}_2/\text{cm}^2$$

In other words, each flood tide in the Upper Basin satisfies only 7.9% of the oxygen demand, and in Hunts Bay only 7.3%. If the water is to be saturated with oxygen, the remainder must therefore be supplied by one or other sources of oxygen. In practice, the atmosphere has been found to be the major source in most of the harbour and saturation only occurs under the very windiest conditions (see Figure 11).

Hence, when the Upper Basin is saturated with oxygen on a very windy day (wind speed 10 - 21 knots), this wind may be responsible for supplying 92.1% of the oxygen demand or $8.84 \text{ mg O}_2/\text{cm}^2$. On windless days (less than 4 knots) when the supply by wind is only 3.6% of that of very windy days (diffusion is directly proportional to the square of the wind velocity - Kanwisher, 1963), the oxygen supply from wind falls to $0.32 \text{ mg O}_2/\text{cm}^2$ and the total supply from wind and tide to $1.08 \text{ mg O}_2/\text{cm}^2$. This leaves a huge deficit between demand and supply of $8.52 \text{ mg O}_2/\text{cm}^2$. Spread over 18 metres of water, this may result in a dissolved oxygen deficit of 4.7 mg/l or a dissolved oxygen level of 1.5 mg/l .

These figures bear close resemblance to the actual conditions we have monitored at stations 5 and 7. That is, on very windy days there may be saturation to all depths while on windless days, the conditions tend towards anoxia. They thus provide further support to the contention that under normal conditions, the D.O. level of the water in the Inner Harbour is determined very largely by the amount of wind and only in a minor way by the tidal flow.

The situation is the same in Hunts Bay and figures may be produced to show that because of its shallow depth, anoxia results even more quickly on windless days. Consequently, any overall reduction of wind or the effects of wind such as wave formation must result in a rapid decline of oxygen level and this, for example, is exactly what has happened with construction of the causeway.

The conditions discussed so far have been regarded as normal; that is, with the water exerting average B.O.D's. However, during plankton blooms, the B.O.D. of the water increases considerably and the total oxygen demand of water and sediment may rise two to three times (except Hunts Bay). When this occurs, the oxygen demand in the Inner Harbour far exceeds the possible supply by wind and tide and anoxia results below the photic zone (see Fig. 12). However, in the Outer Harbour, the supply of oxygen is sufficient to prevent anoxia although there is a significant reduction in D.O. level.

If the oxygen budget of Kingston Harbour (especially the Inner Harbour and Hunts Bay), is to be improved so as to prevent oxygen deficits for all or most

of the time, then the oxygen demand must be reduced and/or the supply increased. At the present level of oxygen supply during average wind conditions, the demand for oxygen by water and sediments at station 7 must be reduced to $7.38 \text{ mg O}_2/\text{cm}^2$ so as to result in a 100% saturation level (see Appendix 2 for calculations). Assuming that the oxygen demand of the sediments will not be reduced until some time after the general oxygen conditions have been improved, the total oxygen demand will then be:

B.O.D. sediment	=	2.29 gm/cm ²
B.O.D. water	=	5.09 gm/cm ²
Total	=	<u>7.38</u> gm/cm ²

For 18 metres depth, this means an average B.O.D. of the water of 2.82 mg/l. At present, the average B.O.D. of the water at station 7 is 4.05 mg/l. In order therefore to accomplish 100% saturation at average wind speeds, the B.O.D. will have to be reduced by 30%. This, however, is a considerable reduction which would bring the B.O.D. of the Inner Harbour water to a condition intermediate between that which now exists in the Outer Harbour and the open sea.

Alternately, instead of reducing the oxygen demand, the supply of oxygen by tidal flow could be improved by opening a channel to the open sea in the eastern end of the harbour. Without at this time considering the merits of such a scheme, the calculations (Appendix 3) show that such an opening would have to improve the oxygen supply by tidal flow from 0.76 mg/cm^2 to 4.54 mg/cm^2 on each flood tide, or an increase to nearly 6 times the present amount for 100% saturation to be achieved under normal wind conditions. However, under this scheme, the increased

tidal flow would have to result primarily in improved circulation of the bottom water, since the oxygen supply would be most needed there. Hence, a surface connection alone between the Inner Harbour and the open sea would almost certainly be inadequate.

The above discussion refers to the Inner Harbour, especially the Upper Basin where oxygen conditions are worst, but the same kind of strategy is needed to improve conditions in Hunts Bay. However, here it is estimated that because of the extremely high oxygen demand of the sediments, reducing or removing the B.O.D. of the water alone would not result in oxygen saturation and an increase in the tidal flow would therefore be necessary to achieve this condition. For example, it is estimated that if the B.O.D. of the water could be halved to 3.62 mg/l, then the tidal flow would still have to be increased to nearly ten times to result in oxygen saturation (Appendix 4). This, could only be done by making a major modification to the present opening.

5. DISCUSSION

From a practical point of view, reducing the B.O.D. in Kingston Harbour must begin with a removal of those factors which give rise to plankton blooms since these blooms exert the greatest oxygen demand which cannot be satisfied with the present oxygen supply. Thus, the nutrient concentrations will have to be reduced to a point where blooms seldom, if ever, occur or, at least, to pre 1962 levels. This must therefore involve a reduction or complete cessation of the discharge of nutrient laden effluents to the harbour.

It is impossible at this stage to quantify this reduction, and more work is clearly necessary to identify the various levels of nutrient input and their effect on concentrations in the harbour. However, lack of these data to date in no way invalidates the point that nutrient reduction is necessary so as to prevent the frequent occurrence of plankton blooms.

But even if plankton blooms are reduced or stopped altogether, oxygen demand by the sediment and water will still exceed the supply throughout most of the harbour. However, since there is no direct way of reducing the B.O.D. of the sediment other than by dredging it out, and since most of the oxygen demand of the water is exerted by the soluble organics, it is at this fraction that the B.O.D. reduction will have to be directed. To do this, a reduction of soluble organic waste discharges to the harbour is essential. However, as is the case for the nutrients, this cannot yet be quantified although it is estimated that its end result must be a B.O.D. reduction of the Inner Harbour water of not less than 30%.

Finally, it should be realised that even if the B.O.D. of the water in the Inner Harbour was reduced by 30%, oxygen deficiency would still occur under windless conditions providing the present tidal circulation is not improved. Since there is no reason to believe that this circulation has at any time been better than it now is (except when the Palisadoes spit was a series of islands), this means that occasional oxygen deficiency has probably been a feature of the Inner Harbour for some time, at least since the present sediments accumulated. Hence, complete saturation under all conditions in the future cannot be expected merely by restoring the water quality.

If tidal circulation in the Inner Harbour is to be improved by opening a channel to the open sea, then considerations other than those concerned with oxygen balance must be taken into account. Since these considerations are outside the scope of the present discussion, they will be returned to later in Part 5 of this report. It should be sufficient to state at this point that although opening a channel could increase the tidal circulation and so improve the oxygen balance, it is likely that certain other effects caused thereby could create new and greater problems in terms of harbour stability. Hence, such a scheme should therefore be approached with great caution.

The incomplete and tentative nature of the results of this oxygen balance study must again be stressed. For, although they indicate the level of the problem and give insight into the kinds of remedies that are possible, they cannot be used for accurately designing corrective measures. That must await a more thorough and comprehensive study including not only a more careful investigation of

the oxygen supply and demand budget but also an inventory of the various discharges reaching the harbour which contribute to its organic and nutrient store.

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(1) Under average conditions, most of the oxygen demand is met by the oxygen supply from the atmosphere and during windless conditions the supply falls off to very low amounts.

(2) Under average conditions, most of the oxygen demand is met by the oxygen supply from the atmosphere and during windless conditions the supply falls off to very low amounts.

(3) Under average conditions, most of the oxygen demand is met by the oxygen supply from the atmosphere and during windless conditions the supply falls off to very low amounts.

(4) Under average conditions, most of the oxygen demand is met by the oxygen supply from the atmosphere and during windless conditions the supply falls off to very low amounts.

(5) Under average conditions, most of the oxygen demand is met by the oxygen supply from the atmosphere and during windless conditions the supply falls off to very low amounts.

6. SUMMARY

(1) The distribution of oxygen in Kingston Harbour is the net result of all those factors which supply oxygen to the system, and all those which use it up. The distribution pattern described in Part 2 indicates that this supply and demand picture is quite different for each section of the harbour.

(2) Based largely on theoretical assumptions, it is estimated that oxygen supply by tidal flow in the Outer Harbour is at least ten times greater than in the eastern end of the Inner Harbour (Upper Basin) and at least thirteen times greater than in Hunts Bay.

(3) However, the other major source of oxygen, diffusion from the atmosphere, is probably the same in the Outer and Inner Harbours although it is likely to be less in Hunts Bay. Diffusion is, however, dependent on wind velocity and this may vary greatly with time of day and season.

(4) It is estimated that under average tide and wind conditions, tidal flow supplies less than 15% of the oxygen to the Upper Basin, while in Hunts Bay, it supplies less than 35%. Thus most of the oxygen comes by diffusion from the atmosphere and during windless conditions, the supply falls off to very low amounts.

(5) Under average conditions, most of the oxygen demand ($> 80\%$) exerted by the water in all sections of the harbour may be attributed to dissolved organics. Hence, the B.O.D. level does not show any relationship to suspended solids except possibly in Hunts Bay.

(6) However, during plankton blooms when the B.O.D. may increase 3 to 6 times normal, most of the oxygen demand ($>50\%$) is exerted by the plankton. It

has been suggested that phytoplankton and zooplankton may be equally responsible for the increased B.O.D.

(7) The B.O.D. of the sediments in Kingston Harbour show a similar trend of values as the water, that is with Hunts Bay being the highest and the Outer Harbour the lowest. However, the actual oxygen demand exerted by the sediments in any one place varies greatly depending on its disturbance. For example, the B.O.D. of the sediment 1 cm. thick in Hunts Bay may increase by more than ten times if it is stirred.

(8) Under normal conditions in the Outer and Inner Harbours, demand exerted by the water per unit area is approximately 2.5 times that exerted by the sediment. In Hunts Bay, however, the oxygen demand exerted by the sediment is 2.65 times that exerted by the water. During plankton blooms, the B.O.D. exerted by the water in the Outer and Inner Harbours increases to 9.76 times that exerted by the sediments, while in Hunts Bay the B.O.D. of the water rises to 0.85 time that of the sediment.

(9) The supply of oxygen at the entrance of the Outer Harbour normally satisfies the demand by water and sediment. In the Inner Harbour and Hunts Bay, however, the demand normally exceeds the supply and there are oxygen deficits.

(10) For supply to equal demand in the Inner Harbour, it is estimated that a 30% B.O.D. reduction of the water is necessary, providing that there are no increases in the oxygen supply. Alternately, if there is

no reduction in oxygen demand, it is estimated that oxygen supply by tidal flow would have to be increased to six times the present.

(11) A 30% reduction in B.O.D. of the water would require an improvement in its quality to a condition intermediate between that which now exists in the Outer Harbour and the open sea near Lime Cay.

(12) A six-fold increase in tidal flow could possibly be accomplished by creating a channel between the eastern end of the harbour and the open sea. However, this flow would primarily have to increase circulation of the bottom water where the oxygen need is greatest. Furthermore, opening a channel could produce some undesirable effects.

(13) In Hunts Bay, reducing the B.O.D. of the water alone would not result in oxygen saturation since so much demand is exerted by the sediments. It has therefore been estimated that if the B.O.D. of the water could be reduced by 50%, then the supply of oxygen by tidal flow would have to be increased to nearly ten times the present to satisfy the demand. It seems that this could only be accomplished by altering the configuration of the opening.

(14) In order to reduce the oxygen demand of the water in Hunts Bay and the Inner Harbour to the necessary levels, priority must be given to removing the causes of plankton blooms. This will obviously involve a reduction in the nutrient levels of the harbour by the control of nutrient-laden discharges to it. Although these reductions cannot be quantified at present, they are believed to be substantial.

(15) But even when plankton blooms are controlled, the oxygen demand exerted by the soluble organics in the water will be too high. Thus, this will also have to be reduced by a reduction in the discharge of all soluble organic matter to the harbour, perhaps by as much as 50% or more.

(16) It is anticipated that even if B.O.D. reduction of the water takes place in the Inner Harbour, periodic oxygen deficiency will occur during windless conditions. In fact this has probably been a feature of Kingston Harbour for some time, at least since the present sediments accumulated on the bottom. Only a complete removal of these sediments or an increase in tidal flow can prevent this condition.

(17) While the results of this study are incomplete and tentative, they have indicated the level of the oxygen problem in Kingston Harbour and hence give some insight into the kinds of remedies that might be possible. Looked at in any way, the problem and its remedies must be regarded to be of major proportions.

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APPENDIX 1

Calculations for the determination of total oxygen demand of water plus sediment at each of the 5 main monitoring stations in Kingston Harbour and in the sea near Lime Cay.

Station 1

B.O.D. normal water = 3.83 mg/l
B.O.D. red-tide water = 16.3 mg/l
Depth = 17m

a) Normal Sediment

B.O.D. water = 3.83 mg/l
B.O.D. sediment = 4.17 mg/cm²
Total = 8.00 mg/cm²

APPENDICES

b) Minimum

B.O.D. water = 4.58 mg/cm²
B.O.D. sediment = 1.20 mg/cm²
Total = 5.78 mg/cm²

c) Maximum

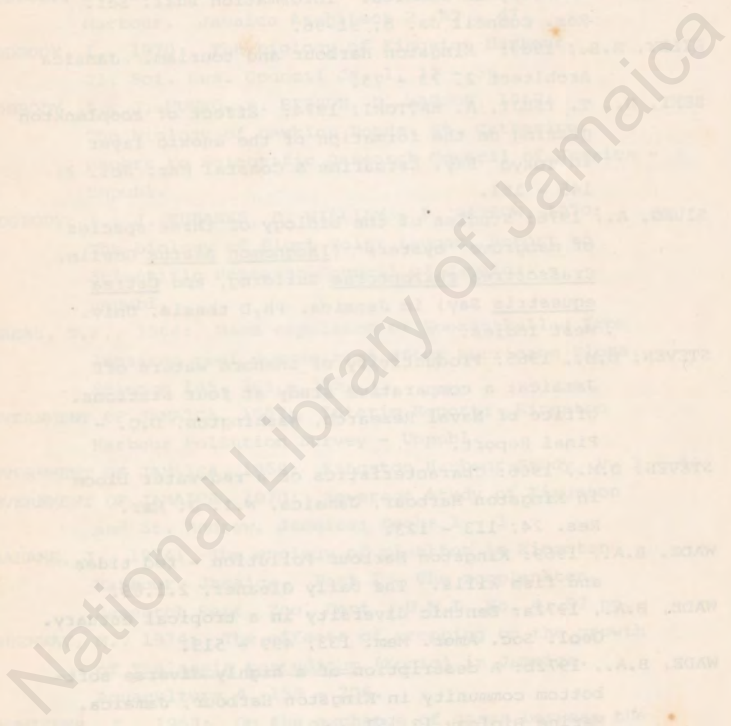
B.O.D. water = 21.19 mg/cm²
B.O.D. sediment = 2.34 mg/cm²
Total = 23.53 mg/cm²

Station 2

B.O.D. normal water = 7.25 mg/l
B.O.D. red-tide water = 16.3 mg/l
Depth = 3m

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APPENDIX 1

Calculations for the determination of total oxygen demand of water plus sediment at each of the 5 main monitoring stations in Kingston Harbour and in the open sea near Lime Cay.

Station 1

B.O.D. normal water = 3.51 mg/l

B.O.D. red-tide water = 16.3 mg/l

Depth = 13m

a) Normal Conditions:

B.O.D. water = 3.51 mg/l x 13m x 10001 : 10000cm²
= 4.56 mg/cm²

B.O.D. sediment = 2.04 mg/cm²

Total = 6.60 mg/cm²

b) Minimum:

B.O.D. water = 4.56 mg/cm²

B.O.D. sediment = 0.30 mg/cm²

Total = 4.86 mg/cm²

c) Maximum:

B.O.D. water = 21.19 mg/cm²

B.O.D. sediment = 2.04 mg/cm²

Total = 23.23 mg/cm²

Station 3

B.O.D. normal water = 7.25 mg/l

B.O.D. red-tide water = 16.3 mg/l

Depth = 3m

a) Normal conditions:

B.O.D. water	=	2.17 mg/cm ²
B.O.D. sediment	=	<u>5.75</u> mg/cm ²
Total	=	7.92 mg/cm ²

b) Minimum:

B.O.D. water	=	2.17 mg/cm ²
B.O.D. sediment	=	<u>0.52</u> mg/cm ²
Total	=	2.69 mg/cm ²

c) Maximum:

B.O.D. water	=	4.89 mg/cm ²
B.O.D. sediment	=	<u>5.75</u> mg/cm ²
Total	=	10.64 mg/cm ²

Station 4

B.O.D. normal water	=	5.05 mg/l
B.O.D. red-tide water	=	16.3 mg/l
Depth	=	12m

Normal Conditions:

B.O.D. water	=	6.06 mg/cm ²
B.O.D. sediment	=	<u>3.33</u> mg/cm ²
Total	=	9.39 mg/cm ²

Minimum:

B.O.D. water	=	6.06 mg/cm ²
B.O.D. sediment	=	<u>0.34</u> mg/cm ²
Total	=	6.40 mg/cm ²

Maximum:

B.O.D. water	=	19.56 mg/cm ²
B.O.D. sediment	=	<u>3.23</u> mg/cm ²
Total	=	22.79 mg/cm ²

Station 5

B.O.D. normal water = 4.58 mg/l

B.O.D. red-tide water = 16.3 mg/l

Depth = 15 m

a) Normal Conditions:

B.O.D. water = 6.87 mg/cm²

B.O.D. sediment = 2.48 mg/cm²

Total = 9.35 mg/cm²

b) Minimum:

B.O.D. water = 6.87 mg/cm²

B.O.D. sediment = 0.36 mg/cm²

Total = 7.23 mg/cm²

c) Maximum:

B.O.D. water = 24.45 mg/cm²

B.O.D. sediment = 2.48 mg/cm²

Total = 26.93 mg/cm²

Station 7

B.O.D. normal water = 4.05 mg/l

B.O.D. red-tide water = 16.3 mg/l

Depth = 18m

a) Normal Conditions:

B.O.D. water = 7.29 mg/cm²

B.O.D. sediment = 2.29 mg/cm²

Total = 9.58 mg/cm²

b) Minimum:

B.O.D. water	=	7.29 mg/cm ²
B.O.D. sediment	=	<u>0.36</u> mg/cm ²
Total	=	7.65 mg/cm ²

c) Maximum:

B.O.D. water	=	29.34 mg/cm ²
B.O.D. sediment	=	<u>2.29</u> mg/cm ²
Total	=	31.63 mg/cm ²

Open Sea

B.O.D. normal water	=	2.0 mg/l
No red tides		
Depth = 13m		

a) Normal Conditions (and Maximum)

B.O.D. water	=	2.60 mg/cm ²
B.O.D. sediment	=	<u>1.22</u> mg/cm ²
Total	=	3.82 mg/cm ²

b) Minimum:

B.O.D. water	=	2.60 mg/cm ²
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Appendix 2

Calculations for estimating the necessary B.O.D. reduction of the water in order to achieve oxygen saturation at Station 7 (Inner Harbour) without increasing the oxygen supply.

$$\begin{aligned} \text{Present saturation level} &= 66.1\% \text{ (Table 7)} \\ \text{Therefore present oxygen supply} &= 66.1 \times 6.2 \text{ mg/l} = 4.10 \text{ mg} \\ &= 4.10 \times 1.8 \text{ l} = 7.38 \text{ mg/cm}^2 \end{aligned}$$

To achieve 100% saturation, oxygen supply must equal or exceed the demand.

$$\begin{aligned} \text{Since sediment oxygen demand} &= 2.29 \text{ mg/cm}^2 \\ \text{Oxygen demand of water must be reduced to} \\ 7.38 - 2.29 &= 5.09 \text{ mg/cm}^2 \end{aligned}$$

$$\begin{aligned} \text{Distributed over 18 m,} \\ 5.09 \text{ mg/cm}^2 &= 5.09 + 1.8 = 2.82 \text{ mg/l} \end{aligned}$$

$$\begin{aligned} \text{Present oxygen demand of water} &= 4.05 \text{ mg/l} \\ \text{Calculated oxygen demand required} &= 2.82 \text{ mg/l} \\ &= 30.37\% \text{ reduction.} \end{aligned}$$

Appendix 3

Calculations for estimating the necessary increase in oxygen supply by tidal flow in order to achieve oxygen saturation at Station 7 (Inner Harbour) without reducing the B.O.D. of the water.

$$\begin{aligned} \text{Present oxygen supply} &= 7.38 \text{ mg/cm}^2 \\ \text{Estimated oxygen supply by tidal flow} &= 0.76 \text{ mg/cm}^2 \\ \text{Therefore oxygen supply by wind} &= 7.38 - 0.76 \\ &= 6.62 \text{ mg/cm}^2 \end{aligned}$$

Since 66.1% saturation is achieved by 7.38 mg/cm² oxygen supply

$$\begin{aligned} \text{100% saturation is achieved by } &7.38 \times 100 \div 66.1 \\ &= 11.16 \text{ mg/cm}^2 \text{ oxygen supply} \end{aligned}$$

$$\begin{aligned} \text{Since oxygen supply by wind} &= 6.62 \text{ mg/cm}^2 \\ \text{Oxygen supply by tidal flow must be } &11.16 - 6.62 \\ &= 4.54 \text{ mg/cm}^2 \text{ for 100% saturation} \end{aligned}$$

$$\begin{aligned} \text{Present oxygen supply by tidal flow} &= 0.76 \text{ mg/cm}^2 \\ \text{Calculated oxygen supply by tidal flow required} &= 4.54 \text{ mg/cm}^2 \\ &= 497.36\% \text{ increase.} \end{aligned}$$

Appendix 4

Calculations for estimating the B.O.D. reduction and increase of oxygen supply necessary to achieve oxygen saturation in Hunts Bay.

Present saturation level = 91.8% = 5.69 mg/l

Therefore present supply = $5.69 \times 0.3 \text{ l} = 1.71 \text{ mg/cm}^2$

Since present oxygen supply = 1.71 mg/cm^2

And oxygen supply by tidal flow = 0.58 mg/cm^2

Oxygen supply by wind must be 1.13 mg/cm^2

If B.O.D. of the water is reduced by 50% to

$3.62 \text{ mg/l} = 3.62 \times 0.3 \text{ l} = 10.86 \text{ mg/cm}^2$

And oxygen demand by sediments = 5.7 mg/cm^2

Then total oxygen demand will be $5.7 \times 1.07 = 6.78 \text{ mg/cm}^2$

Since oxygen supply by wind = 1.13 mg/cm^2

Oxygen supply by tidal flow must be

$6.78 - 1.13 = 5.65 \text{ mg/cm}^2$

Present oxygen supply by tidal flow = 0.58 mg/cm^2

Oxygen supply by tidal flow required

= 5.65 mg/cm^2

= 874% increase.