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Smithsonian Institution
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Errata

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Page	Error
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PREFACE

During 1973 the Smithsonian Institution's Office of International and Environmental Programs undertook a case study of the Volta Lake in Ghana. This was one of a series of case studies, carried out for the U.S. Agency for International Development, designed to better understand the environmental impacts of various development projects or situations. The purpose of these studies was to extract lessons which could be translated into guidelines to orient future development, in order to prevent costly and avoidable environmental impacts. The case study approach was chosen in view of the proven advantages of obtaining detailed understanding of a specific development. The Volta Lake was seen to constitute an excellent case study opportunity for a review of the environmental impacts of impounding a tropical river. Impacts in the impoundment area have been well researched and documented, and they are not dissimilar from the known impacts of other African man-made lakes. And like other hydropower schemes, the benefits have been very substantial.

Preparatory to undertaking the case study, Dr. I. Eugene Wallen, then Director of the Office of Environmental Sciences, visited authorities in Ghana in 1971, to develop a mutually satisfactory study agenda. On the basis of discussions with Mr. E. L. Quartey, Chief

Executive of the Volta River Authority (VRA), other officials of the VRA, and scientists in the government and universities, an agenda was developed and subsequently approved at all levels in the Ghanaian government. The case study was to focus on the following areas, which were seen to complement and contribute to ongoing research in the Volta Lake: lake geology, groundwater related hydrology, mineral cycling, plankton, aquatic plants, fish nutrition and production, lake bathymetry, water supply and sewage, and biological control of waterborne diseases. Expanded descriptions of the study objectives and scope are presented in the introduction. At a later date, the Volta River Authority agreed to include a review of the socio-economic costs and benefits of the project; however, this task was not completed as of the drafting of this preliminary document.

Following an August, 1972, visit by Mr. Peter H. Freeman, Smithsonian project manager for the case study, during which an overview of the availability of study materials was made, work was begun in Washington, D.C., on assembling an annotated bibliography on the hydrobiology of the Volta Lake. Published and unpublished materials collected in Ghana and Washington were incorporated into a bibliography prepared by Mr. M. A. Aziz. It appears in the appendix to this document. In October, 1972, a number of U.S. scientists met at a workshop in the Smithsonian Institution to determine the possibilities of constructing a mode of the Volta Lake, in order to provide a structure for organizing and interpreting existing information. An analytical modeling

exercise was not found to be feasible, largely because of serious gaps in information on the lake's mineral cycle. Field visits by U.S. and Canadian scientists were then arranged.

In consultation with the Volta River Authority, scientists was particular competence in the areas of the study agenda were selected. The names of these scientists and their study areas appear below. During the period December, 1972 to August, 1973, they visited the Volta Lake, met with officials of the Volta River Authority and other Ghanaian institutions, and drafted reports on their work. These were organized into a preliminary comprehensive report by Peter H. Freeman, which was then reviewed by the participating scientists and the Volta River Authority. Their reactions are incorporated into the present report.

Dr. Harold E. Thomas 1339 Portola Road Woodside, California	Lake geology and hydrology
Dr. A.M. Beeton Associate Director of the Center for Great Lakes Studies Professor of Zoology University of Wisconsin Milwaukee, Wisconsin	Evaluation of plankton
Dr. Daniel A. Livingstone Department of Zoology Duke University Durham, North CArolina	Mineral cycling
Dr. John J. Gaudet Department of Biological Sciences Kenyatta University College Nairobi, Kenya	Aquatic plants
Dr. Julian D. Reynolds Department of Zoology University of British Columbia Vancouver, Canada	Fish nutrition and production

Mr. William S. Robinson Senior Vice President Towill Inc. 608 Howard Street San Francisco, California	Lake topographic survey
Dr. John Boland Department of Geography and Environmental Engineering The Johns Hopkins University Baltimore, Maryland	Water supply and sewage
Dr. Lloyd Knutson Insect Identification and Beneficial Insect Introduction Institute Agricultural Research Service USDA, Beltsville, Maryland	Biological control

An international, multidisciplinary study of this kind requires the interest and willing collaboration of many institutions and countless individuals. All of the contributing scientists serving under the auspices of the Smithsonian Institution, participated in the study without remuneration, and some utilized vacation time to undertake the work. The Smithsonian Institution is deeply appreciative of their voluntary contributions. On behalf of the contributing scientists, the Smithsonian Institution gratefully acknowledges the ready collaboration and time extended to them by the many scientists, technicians, and government officials in Ghana, who are too numerous to mention here. They are named in acknowledgements of the individual reports submitted to the Volta River Authority.

The support and collaboration of the Volta River Authority was essential for the conduct of the study. The VRA arranged itineraries, transportation and lodging for the visiting scientists,

and freely shared unpublished and published information stored in its library, as well as at the Volta Lake Research Project headquarters in Akosombo. The continuing interest and help of Mr. E. L. Quartey, Chief Executive, and Mr. E.A.K. Kalitsi, Executive Secretary, is especially appreciated. The Smithsonian Institution also is appreciative of the willingness of the VRA to permit a critical assessment of the ecological and other impacts of the Volta Lake by outside scientists, whose views and perceptions are fresh but at the same time necessarily imperfect.

Special appreciation is extended to the Smithsonian staff who helped in the preparation of this work. M. A. Aziz, research assistant, undertook the laborious annotation of hydrobiological work done on the Volta Lake, and the compilation of the flora and fauna of the lake. He also organized the first workshop which addressed the possible construction of a model of the lake's ecosystem. Kenneth Mowll, research assistant, helped arrange travel for the consultants. Helen D. Davidson also developed travel arrangements, typed the preliminary version of the annotated bibliography, and clean typed many of the consultants' reports. Venka MacIntyre typed the present comprehensive version and made valuable editorial suggestions.

A final debt of gratitude is due to the many Ghanaian and international scientists whose work on the Volta Lake was a necessary prologue to this case study.

TABLE OF CONTENTS

	Page
PREFACE	ii
LIST OF TABLES	xiii
LIST OF FIGURES	xv
Part	
I SUMMARY AND SYNTHESIS	1
Lake Geology	1
Groundwater Geology and Related Hydrology	3
Lake Topographic Survey	5
Mineral Cycling	7
Plankton	11
Aquatic Plants	12
Fish Nutrition and Production	16
Water Supply and Sewage	21
Biological Control of Schistosomiasis and Other Important Diseases	27
II SURVEY OF THE VOLTA LAKE AND CERTAIN ENVIRONMENTAL IMPACTS	31
1. Introduction	31
2. Lake Geology and Groundwater Hydrology	41
The Geologic Environment of Volta Lake	41
Effect of Volta Lake upon the Geologic Environment	43
Reservoir sedimentation	44
Seismic effects	46

CONTENTS--Continued

Page

2. Lake Geology and Groundwater Hydrology continued

The Hydrologic Environment of Volta Lake 47
Precipitation inflow vs. evaporation outflow 48
Possible climate change caused by Volta Lake 49
Surface inflow to and outflow from the lake 49
Subsurface inflow to and outflow from the lake 51
The groundwater resource 52
Groundwater development 53
Groundwater management 56
Groundwater research 59

3. Lake Bathymetry and Related Surveys 61

Introduction 61
Bathymetric Survey Trial 63
Sedimentation Surveys 66
Area-Capacity Calculations 71
Navigation and Charting 78
Seismic Considerations 82

4. Changes in Mineral Cycling Associated with the Formation of the Volta Lake 87

Introduction 87
Mineral Cycling 88
Geochemistry of African waters 90
The Volta Lake 93
Internal cycling within the lake 93
Changes in mineral cycles below the dam 99
Potential salination problem in the irrigation of the Accra Plains 102
Conclusion 103

CONTENTS--Continued

Page

5. Plankton in the Volta Lake 105

Introduction 105
Pertinent Physical and Chemical Observations 106
Phytoplankton 109
Productivity and Trophic Conditions 114
Proposed Kinds of Research 119

6. Aquatic Weeds in Volta Lake and Their Control 122

Introduction 122
Objectives 124
Plant Succession on Volta Lake 124
Pre-impoundment 124
Post-impoundment, early stages 125
Post-impoundment, later stages 127
Present Aquatic Flora 129
Emergents 129
The floating vegetation 135
The submerged vegetation 136
The drawdown area 137
Lake Volta Compared to Lake Kariba 139
Weed Problems 140
Substrate for bilharzia snails 140
Interference with fishing and transport 144
Beneficial Aspects of the Weeds 144
Fishing 144
Nutrient cycling 145
Trapping of sediments 147
Composting 148
Grazing 149
Control Measures Past and Present
Weed clearance for bilharzia snail control 150
Clearance of fish channels 154
Biological control 155
Environmental control 156
Cost of Control 156
Chemical control 156
Mechanical control of weeds at Ampem 158
Possible Directions For Future Weed Control
Programs 160
Weed control 160
Weed surveys 162
Weed biology 162

CONTENTS--Continued

Page

7. Fish Nutrition and Production 164

Introduction 164
Primary Production and Fish Nutrition 165
Nutrition Studies 166
Pellonula Trophic Web 171
Fish Production 173
Determination of the Lake's Productivity 176
Future Fish Productivity of the Volta Lake 179
Lake Fertilization to Enhance Fish Production 185
Summary 190
Research Problems 191

8. Water Supply and Waste Assimilation Aspects of Volta Lake 195

Introduction 195
Managing Environmental Resources 196
Characteristics of environmental resources 196
Resource management 199
The Volta River project 201
Water Supply Services 206
Withdrawal energy requirements 207
Withdrawals from tributary streams 209
Withdrawals from the lake 211
1) Withdrawals for human settlements in the lake drainage basin 211
2) Withdrawals for irrigation and industry in the lake basin 216
3) Withdrawals for uses outside of the lake basin 218
4) Management implications of lake withdrawals 219
Withdrawals from the Lower Volta River 221
Waste Assimilation 222
Managing waste assimilation services 226
Conclusions and Recommendations 228

CONTENTS--Continued

	Page
9. Biological Control of Schistosomiasis and Other Parasitic Diseases	233
Introduction	233
The Four Major Parasitic Diseases Associated with the Volta	234
Onchocerciasis (river blindness)	234
Malaria	235
Sleeping sickness (Trypanosomiasis)	236
Schistosomiasis (Bilharziasis)	237
Detailed Comments on Schistosomiasis	238
Present control methods	238
Rationale for use of biological methods of control	239
Possible objections to biological control	240
Requirements for the development of biological control programs	241
Major Possibilities for Biological Control of Schistosomiasis, with Reference to Ghana and Volta Lake	241
Natural Enemies of Intermediate Host Snails	242
Predaceous and parasitoid insects	242
Predaceous and competitor snails	244
Predaceous fish	244
Waterfowl	245
Genetic Manipulation of Snail Populations	245
Natural Enemies of Schistosome Cercariae and Miracidia	246
Control of Intramolluscan Stages of Schistosomes	247
Relationship of Aquatic Weeds and Schistosomiasis	248
General Conclusions and Recommendations	250
REFERENCES CITED	252

CONTENTS--Continued

APPENDICES

Page

1. Notes on Calculations of Nutrients Trapped by Water Weeds 264

2. Field Observations Made on the Volta Lake by J. D. Reynolds During May, 1973 266

3. Annotated Bibliography of the Hydrobiology of Volta Lake 275

   Index of Authors 327

4. Partial Inventory of Flora and Fauna 329

LIST OF TABLES

Table		Page
1.	Borehold Test Data Throughout Ghana	54
2.	Reservoir Areas and Volumes, Volta Lake	74
3.	Weed Communities in Riverine Lagoons Before Impoundment	125
4.	Comparison of Species Composition of Sudd on Lake Volta	126
5.	Drawdown Zone Plant Species on Volta Lake	128
6.	Comparative List of Common Emergent Aquatic Plants Found in African Swamps and Lake Edges	130
7.	Depth and Duration of Flooding of Different Species in the Nile Swamps	131
8.	Generalized Plant Zonation on Volta Lake	134
9.	Effect of Flooding on Some Drawdown Species in a 900 m^2 Plot	138
10.	Comparison of Major Changes in Aquatic Weeds During the First 10 Years in Two African Man-Made Lakes	140
11.	Distribution of *Bulinus* Snails on Substrates Sampled over 24 Months on Volta Lake	142
12.	Comparison of Fish in Different Littoral Habitats	145
13.	Estimate of Nutrients Trapped in Aquatic Weeds on Volta Lake	146

TABLES--Continued

Table

Page

14. Nutrients Lost in Outflow from Volta Lake 147

15. Percentage Composition on a Dry Weight Basis of Some Common Emergent Aquatic Weeds on the Nile 150

16. *Bulinus* Snails Found in Ampem Study Areas 153

17. Invertebrate Species Composition on Savannah Tree, Pawmpawm Bay (on Branch 3 cm Diameter, 60 cm in Length) 268

18. *Pellonula* Experimental Catch Data 273

LIST OF FIGURES

Figure		Page
1.	Fathometric profile, Volta Lake	65
2.	Tentative location of proposed sedimentation ranges	68
3.	Plant zonation on Volta Lake	133
4.	Erosion of a lake shore	133
5.	Aquatic weed growth near Ampem	143
6.	Ampem shore cleared of weeds (August)	152
7.	*Pellonula* food web	172
8.	Fish population developmental sequence: simplified typical food chains, Volta Lake	181

PART I

SUMMARY AND SYNTHESIS

The following section summarizes and integrates the contents of the various reports submitted by the participating scientists. The full reports are presented in Part II of this document.

Lake Geology

Existing published and unpublished data were reviewed, but original field survey work on the geology of the region was not undertaken. The lake lies in a sedimentary basin which extends over 40 percent of Ghana. The principal component is the Voltaian Formation, whose upper part consists of horizontal to gently dipping, massive beds of sandstone. These form escarpments in excess of 300 meters above sea level in extensive areas along the northern and eastern rims of the basin, and a distinct higher escarpment at the south rim. Lower lying surficial rocks include shale, mudstone, siltstone, arkose, sandstone, and conglomerate, which have few outcrops. The Voltaian Formation is underlain by pre-Cambrian granites, metamorphosed sediments and lavas, including the Togo quartzites that outcrop at the Akosombo

Dam. Mineral resources flooded by the dam are of limited economic value: limestone, in the bed of the Afram River and on the eastern flank of the Volta Gorge, and sands and gravels along the Volta River and its tributaries.

The lake has added weight, which fluctuates seasonally, to underlying rocks. When filled to capacity the 165 cubic kilometers of water in the reservoir weigh 165 x 10^9 metric tons; this is reduced by about 25 x 10^9 tons during low water. The seismic effect of the added weight is not known. Three earthquakes of intensity 5 on the Modified Mercalli scale have occurred since the filling of the lake began in 1964. In Ghana the zone of major seismicity is in a triangle extending southeastward from the Togo quartzite. Two of the earthquakes mentioned above had epicenters offshore from Accra, while the third epicenter was 40 miles south of Akosombo near Koforidua. There have been no special measurements undertaken to determine the seismic effects associated with the reservoir filling, although a program has been planned by the Geological Survey Department of Ghana.

Sedimentation rates in the reservoir are not known, but sedimentation has never been judged to be a problem, given the lake's large volume. However, notwithstanding the relative unimportance of the sedimentation, rates should be monitored. Robinson and Reynolds* note that sedimentation will occur primarily as delta build-up by coarse sediments in the mouths of major tributaries.

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*The full names of participating scientists, and their study areas, appear in the Preface.

Groundwater Geology and Related Hydrology

Because of the absence of pre-impoundment and later data on groundwater in the lake region, it is not possible to assess the effects of the lake on groundwater movement, or to judge the contribution of this source to the reservoir. The water table in and near the drawdown zone is obviously influenced by seasonal fluctuations in reservoir level, but this is probably significant only to crop production. Robinson suggests that seismic sub-bottom profiling could generate information on the geologic formations underlying the lake--perhaps to a depth of as much as 300 to 400 feet. The geologic and geophysical data obtained could be applied to the study of groundwater, as well as seismicity, when supplemented by existing and new data.

Available data suggest that loss by evaporation from the lake surface is nearly balanced by gain due to rainfall upon that surface (55 to 60 inches average annual rainfall, and 57 to 70 inches average annual evaporation). Thus, the main hydrological variable for the lake appears to be run-off. Existing data indicate that the mean annual flow of the river prior to construction of the dam was at least 36 km^3, approximately 43 percent of which originates in Ghana. However, total average annual run-off in the basin varies considerably from year to year. In 28 years the recorded run-off was within 10 percent of the mean in only three years, more than 25 percent below the mean in eight years, and 25 percent above in eight other years. The relative recency of continuing hydrologic observations in the Volta Basin (since 1959) has handicapped planning.

The determinations of possible climatic changes caused by the lake will require several more years of data. Several Smithsonian consultants noted reports of high offshore nocturnal winds at Ampem, on the southern shore of the Afram arm. These may be a consequence of nighttime convective air currents over the water surface which draw cooler air descending from the mountain range south of that shore. But they could also be a consequence of the Föhn effect of the southerlies descending the same slopes into the Afram arm. The desiccating effects of these winds may be important to crop production and may contribute to total evaporation from the reservoir surface.

A review of groundwater surveys and programs indicates that groundwater may be important chiefly for rural village water supply, but that potential production from aquifers is generally too low to justify the installation of motor pumps or for additional uses such as irrigation. The Voltaian sedimentary basin is poorer than average for Ghana, and the Dahomeyan Basin, underlying the Accra Plains, has the lowest potential. Eight research wells there, however, have averaged 600 to 1500 gallons per hour, equivalent to only 0.04 to 0.1 acre feet per day. In general, the average yield of wells may be greater than re-charge rates, due to the impermeability of the subsoil above aquifers. Wells are not presently monitored, however.

Lake Topographic Survey

Robinson reported on the results of a fathometric survey trial with an electronic depth recorder, evaluated the adequacy of existing topographic information on the reservoir, reviewed the survey needs for sedimentation, and formulated recommendations for surveys and mapping which would be desirable for the purposes of more accurate determination of area-capacity, navigation, sedimentation build-up, and seismic movements.

Profiles of the lake bottom were obtained for the area extending 40 miles north from the dam, using a Raytheon DE 719 (200 kc) Survey Depth Recorder with a rated accuracy of within plus or minus one foot. The profiles were uncontrolled, and horizontal location was made by visual reference to map features. Robinson concluded that this sonar system would be totally satisfactory for obtaining bottom profiles of the lake. Although submerged vegetation was recorded on the charts, it did not confuse the registration of the bottom.

At points with verifiable elevations, the comparison of the profiles with existing 1:50,000 topographic maps, showed differences from map elevations of 30 to 50 feet* in most instances. This has important implications for computations of the lake's area and storage capacity. A ten-foot error on the minus side at the 270-280 foot level could mean a reduction of 20 percent in capacity and of 405 square miles in area. As long as the lake's water is to be used only for hydropower generation, this difference is not important.

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*The English system of measures has been used in past surveys of the lake.

But more accurate area-capacity curves will be needed, particularly at the 248 to 276 foot "live storage" level, if additional uses are to be made of the water. Also, the inherent inaccuracies in existing topographic maps make them unsuitable for shoreline and foreshore definition in most of the lake. Given the considerable area of the foreshore due to shallow gradients, these inaccuracies introduce errors into the computation of evaporation and in the total surface of the drawdown zone. As mentioned later, this zone is of increasing importance to the lake's fisheries.

To obtain more accurate data on the lake's shoreline and foreshore in the critical zone (e.g., 248 to 276 foot range), two alternatives are suggested. Both would utilize existing 1:50,000 aerial photomosaics of the lake, constructed in 1971, for the Volta Lake Research Project. The first would be to take black and white aerial photographs (panchromatic or infrared) at a relatively high altitude, with a relatively wide angle lens (3 1/2 inches focal length), at a time when the lake level is drawn down to the 255-foot elevation. Simple stereoscopic analyses would permit interpolation of the 5-foot contours and extrapolation of the 250-foot contour, which could then be transferred to the photomosaics. Should the lake not be lowered to the 255-foot level, the second alternative would be a bathymetric survey to define bottom contours at 5-foot intervals down to 248 feet. For steeper shores, new mapping is not needed, since the existing 1:50,000 topographic maps give sufficient accuracy.

The need for bathymetric surveys in the northern reaches of the lake to aid navigation was anticipated by Robinson. Presently drowned emergent trees serve as channel markers, but the decay of these and the build-up of sediments at the mouths of tributaries will eventually make surveys necessary. Bathymetric surveys should be undertaken of all proposed navigation channels. Tributary delta build-up should not significantly affect the reservoir storage capacity; however, Robinson agrees with Thomas that baseline data on sedimentation should be obtained, so that at some future date the impact of sedimentation can be projected for the future operations of the reservoir.

Although the dam structure is presently monumented so that downstream deflection or slip can be monitored by conventional surveying methods, permanent strain in the dam area caused by earthquake effects should be monitored. The installation of relatively inexpensive tiltmeters at the lower levels of the power structure and spillways, to supplement existing seismometers, is recommended.

Mineral Cycling

Changes in mineral cycling in the reservoir area and below the dam were reviewed by several of the Smithsonian consultants on the basis of existing data. They agreed with most Ghanaian scientists that the Volta Lake is oligotrophic, that is, low in mineral nutrients. The consultants judged, however, that fertilization of the lake to increase its productivity is not feasible.

An accurate picture of mineral cycling in the lake cannot be obtained because key data have not yet been developed, especially on the mineral inputs from surface inflow to the lake and from rainfall, the two major sources of minerals external to the lake. Livingstone noted also that the absence of pre-impoundment water chemistry measurements below the dam prohibits use of subsequent water chemistry data for deducing the downstream changes in the hydrological mineral cycle.

Beeton posed a number of questions that must be answered before the mineral cycle of the lake, and therefore its productivity, can be understood: Are major nutrients (and accessory growth substances) in chemical forms which can be used by algae? Does bacterial activity facilitate mineral recycling to plants? What is the influence of the terrestrial environment and especially the drawdown zone? What are the magnitudes of contributions from tributaries, direct run-off, and precipitation? Are nutrients lost to sediments and/or returned from sediments?

The last question above is posed by Livingstone in relation to the question of fertilization of the lake, and he considers it probable that phosphorus may be abundant in sediments, but not in the water.

Deeper water appears to have higher mineral concentrations. Data developed at Ajena in south lake indicate the existence of a small "puddle" of nutrient-rich, oxygen-poor water whose reducing conditions may lead to increasing levels of iron and magnesium. This may adversely affect the quality of spillway water. However,

only the deepest five percent of the lake's volume would be characterized by this condition. Water movement at the deeper levels could possibly diffuse the minerals, and a further question posed is the probable mixing of nutrients by means of internal waves. These are a common feature of stratified lakes, such as the Volta.

The downstream impacts of the dam on the nutrient cycle are not judged to be great, although declines in river fish production have been reported. The nutrient load of the river is not high, as is indicated by the decline in the lake's productivity with stabilization. The enrichment of estuaries and floodplains, prior to impoundment, was certainly not on the same order as that of the Nile River. For the same reason, the impact is not judged significant offshore, where nutrients are provided primarily by up-welling water. However, the damming of the river and stabilization of its flow have probably had some impact offshore, to the extent that seaward run-off during the rainy season prior to impoundment, would have tended to prevent up-welling.

Aquatic vegetation is judged by Gaudet to be a significant element in the lake's mineral cycle. Emergent weeds recycle a small but significant portion of nutrients such as iron, nitrogen and phosphorus, which otherwise would be removed in outflowing water or trapped in mud and silt. These emergents are essentially drawdown zone flora, in an approximately 100-meter wide strip along most of the lake edge. Gaudet estimated the amounts of minerals trapped in three dominant species--*Ceratophyllum demersum*,

Pistia stratiotes, and *Polygonum* spp. Out of an estimated 15,569 m.t. trapped, 31 percent would be nitrogen, 30 percent potassium, 21 percent iron, and eight percent phosphorus. The total represents more than a third as much as the 41,000 m.t. of minerals that he estimates to be lost annually in the outflow. The significance of the phosphorus trapped in aquatic vegetation is underlined by the inexplicably low levels of phosphate that have been found in the lake's water since 1966. Phosphate was not present in the upper 20 meters at Ajena in January-March, 1973, while in 1970-1972 levels at Ajena were only 0.02 to 0.05 mg/l. (Water chemistry at Ajena is assumed to be representative of the lake's open waters.)

The significance of minerals trapped in drawdown zone vegetation is implicit in the analyses made by Reynolds of fish nutrition. The large store of nutrients in the drowned vegetation and trees has been rapidly released and utilized, and fish nutrition is increasingly dependent upon insects, benthic organisms, plankton, and primary production in the drawdown zone. A portion of the minerals stored in drawdown zone weeds is eventually converted to fish flesh, and it is in this zone and adjacent portions of the littoral that the major catch of *Tilapia* spp. is made.

Plankton

Plankton also figures in the lake's nutrient cycle. Since 1966 and relative stabilization of the lake, phytoplankton populations peak in October and November, immediately after maximum flood in the lake. In Beeton's opinion, that abundance is closely tied to the nutrient inputs during the flood period, and not to mixing of nutrients from bottom waters into the euphotic zone during the December to February Harmattan winds, as some researchers have hypothesized would occur. Determination of the role of the phytoplankton in nutrient cycling must, however, await research on the turnover time of the population and the extent of cropping by zooplankton and fish.

More is known about phytoplankton in the Volta Lake than zooplankton. Research has tended to be concentrated at Ajena in the south, while other areas of the lake have been sampled only infrequently and some areas not at all. Some research results are not comparable because of differences in sampling equipment.

Phytoplankton diversity has increased from 34 to 84 taxa with the formation of the lake. Blue-green algae (*Anabaena*) were dominant in the river prior to impoundment. During the 1964 to 1966 period of lake filling and maximum instability, different algae assumed dominance. By 1969, the blue-green alga, *Lyngbya limnetica*, had emerged as the dominant species. There is no agreement among researchers as to which portions of the lake are richest in algae, but data tend to support the idea that the arms and shallow waters are more productive than the deep, open waters.

Phytoplankton have been found to comprise nine percent of the food of fish and must provide food for many invertebrates as well as contribute to the periphyton food source.

The zooplankton peak coincides with the October to November phytoplankton peak. Local abundance and time of abundance vary considerably, however. Shallow areas may be nursery zones for zooplankton. By weight rotifers have comprised 80 to 90 percent of the samples, ciliates four to 15 percent, and crustaceans six percent. Little information is available on planktonic crustacea as food for larval and juvenile fish, although zooplankton has been found to comprise one percent of fish food.

As to the influence of phytoplankton on dissolved oxygen concentrations in the lake, Beeton noted that while decrease in hypolimnetic oxygen in temperate lakes can be associated with increasing eutrophy as plankton decays, in the Volta Lake low dissolved oxygen has been caused by decay of terrestrial vegetation.

Aquatic Plants

The role of aquatic plants in the lake's nutrient cycle is discussed above in the summary on mineral cycling. Plant succession, weed problems, beneficial aspects of weeds, control measures, and possible directions for future control programs, were also reviewed.

The principal features of succession of the lake's aquatic vegetation are:

a. The short-lived development of sudd, or floating weeds, shortly after impoundment, which, however, did not become a problem of the same magnitude as has occurred on Lake Kariba.

b. The development of flood-tolerant species in the drawdown area.

c. Rapid growth and spread of the floating weed, Pistia, during 1965-1968, followed thereafter by a cessation of spreading and decrease in population. This is explained by the reliance of Pistia on dissolved nutrients, which were initially present in relatively high concentrations, but have since declined. Also increasing exposure to wind, turbulence, wave action and natural predation have acted to control Pistia. Pistia is, nevertheless, well established in the lake.

d. The appearance of Vossia spp. as the dominant emergent plant in the drawdown area. Reasons for this are its relative resistance to wind and wave action; vigorous vegetative propagation; rapid growth; hollow stems adapted to flotation; and relative resistance to the burrowing mayfly (Povilla adusta), which gives Vossia an advantage over its Polygonum competitor. Vossia also is relatively resistant to herbicides, and has needle-like hairs on its leaf sheath that discourage grazing

and make hand-cutting difficult. Finally, Vossia can form sudd, and thereby spread to colonize the lake shore drawdown zone.

e. The appearance of Ceratophyllum as the dominant submerged plant, forming beds with abundant populations of the Bulinus snail.

f. Relative stabilization in aquatic plant succession as of 1973.

Two major problems are associated with water weeds on the lake. The most important one is that the snail vector of urinary schistosomiasis is especially abundant in beds of the dominant submerged plant Ceratophyllum. In its dense beds these snails feed, deposit eggs, and find protection from predators, intense sunlight, and fluctuations in lake level. A second problem is that Ceratophyllum and other weeds interfere with navigation and the operation of outboard motors.

The main benefit of the weeds is their contribution to fish production as substrate for periphyton, and as spawning and breeding habitat. Vossia beds are a productive fish habitat, and have been found to yield 255 kg/ha of fish biomass, distributed among 38 species, but with cichlids (which include Tilapia spp.) dominant. Ceratophyllum beds are relatively unproductive. The weeds also can trap sediments, which in areas of drawdown agriculture may be washed into the water in considerable quantities, especially if wave action is great. Some farmers

plow burned Vossia back into the wave-washed soil.

There is a potential for the use of aquatic weeds as compost and for grazing. Used as compost, the weeds would recycle to the soil those nutrients lost from farmland by erosion and leaching, as well as contribute organic matter, which is low in the soils of the drawdown zone. Local cattle have been observed to graze in the drawdown area, where they prefer Echinochloa pyramidalis to the dominant Vossia.

Weed control and clearing experiments carried out at Ampem were reviewed by Gaudet. The major objective of these trials was to find a way to combat schistosomiasis by controlling the habitat of the snail vector. There was little success in controlling Ceratophyllum, the problem weed.

It was found that herbicide control of all emergents was effective if these were young plants. However, repeated applications were necessary, especially to control Vossia. That plant had to be literally pulled up by the roots to achieve effective control, which moreover is only temporary since it readily propagates in cleared areas. Herbicides were not effective on mature plants of Vossia and other emergents, and the use of a number of herbicides had the disadvantage of later inhibiting growth of susceptible drawdown crops, such as tobacco and tomatoes. Ceratophyllum was controlled by the more expensive herbicide "fenac" ($400/ha treatment cost), with the added disadvantage that this chemical is one of the herbicides that inhibits crop growth.

This work and later trials have shown that the only weed-clearing technique on Volta Lake which has worked well consists of burning, cutting, and hoeing. This proved to be fairly labor intensive; for initial clearing 27 man-days per hectare were needed and to maintain a plot weed-free required an average of 22 man-days/ha/year. Maintenance required cutting the vegetation to soil level just ahead of the rising water. Conflicts were posed since this time of the year--the rainy season--is also the period of peak activity on farms. This approach is not effective for Ceratophyllum, for which the only alternative seems to be a combination of herbicide treatment and physical removal. More knowledge is needed on the biology of this important weed. Also, trials with new herbicides which are cheaper and ecologically safer should be undertaken. The only important weed known to have natural controls is Polygonum, which is attacked by the burrowing mayfly. Polygonum will probably come under increasing attack to the extent that the softer portion of drowned vegetation, which the mayfly also has attacked, has been steadily decreasing.

Fish Nutrition and Production

The original river fish were primarily benthic feeders (e.g., mormyrids and mochocids) and insectivorous, surface-feeding characids (e.g., Alestes spp.), and schilbeids (e.g., Eutropius spp.). Following impoundment an extensive reservoir was created, which for the purpose of reviewing changes in fish,

can be considered in two major parts: north and south, with a transition zone that is many miles wide and shifts with the seasons. The northern arms are shallow, narrow and dominated by extensive areas of flooded savannah bush. The region resembles the Niger central delta in its strongly riverine quality. The southern lake is the area generally thought of as the Volta Lake. It has undergone more pronounced changes than the northern portion.

Immediately following closing of the dam in May, 1964, and a precipitous drop in dissolved oxygen, there was a mass die-off of the bagrid Chrysichthys, and a permanent decline of most mormyrid species. The mormyrids have apparently been limited by the lower dissolved oxygen level in the lake's water, especially just after closure. Although now about 90 to 100 percent saturation, the level is lower than the 110 to 170 percent saturation that characterized the river. Disappearance of their rocky riverine breeding habitat has also been cited as a reason. While insectivores have remained an important component of the lake's fishes, species composition has shifted to a dominance of clupeids and a relative decline of insectivorous characids, schilbeids, and bagrids, especially in the south of the lake. However, species in these families which are facultative feeders, able to exploit the wider range of food resources created by the lake, do comprise part of the south lake's fish population. In the northern arm they remain dominant in catches.

With the creation of the lake, the appearance of new food sources not important in the river, namely water weeds, plankton and periphyton (aufwuchs), favored the relative increase of phytophagous and planktivorous species, and species able to exploit the invertebrates of the abundant periphyton that developed on drowned vegetation and water weeds. Cichlids, which include the commercially important Tilapia spp., increased greatly. In the north lake, shallow foreshore gradients have apparently resulted in considerable benthic production, and the mudsucking Labeo is an important commercial fish there. However, in terms of weight, the pelagic Pellonula sp., which feeds on aquatic insects living in the periphyton and on zooplankton, is the dominant fish on the lake. Although not commercially fished, its predator, Lates, is now the second most important fish caught in terms of weight. Trophic webs are complex, as a result of the lake's changeable environment, diversity of food sources, and fluctuations in types and abundance of food. Only the more opportunist species in feeding, behavior, and reproduction can flourish in such an environment. These circumstances complicate the assessment of fisheries.

Certain major characteristics can be discerned which influence considerations of the lake's productivity. The approximately 80,000 ha surface of the drawdown area has become very important to the lake's fish productivity, following the decline of the nutrient sources in the drowned vegetation and the stabilization of the lake's ecosystem at an oligotrophic level.

Average fish biomass in the lake's littoral has been measured at 120 kg/ha, while the lake's average level of sustainable fish yield is estimated at 35 to 40 kg/ha. The heavily fished *Tilapia* spp. are caught primarily inshore.

The succession of water weeds leading to the dominance of *Vossia*, and the less abundant but important *Polygonum*, have favored fish production in the drawdown zone. These weeds do not block the sunlight. They provide substrate for periphyton, refugium for juveniles (mainly in the northern lake, in Reynolds' opinion), and the *Polygonum* is attacked by an important fish food, *Povilla adusta*, the burrowing mayfly. With the decrease in the softer parts of drowned trees as a result of *Povilla* attack, the *Polygonum* becomes more important as an alternative food source for this invertebrate, and correspondingly *Polygonum* weed beds become more important as feeding habitats for fish.

The lake's fisheries harvest greatly exceeded the 18,000 t/year estimates made prior to impoundment, especially during maximum production, which was short-lived. Catch peaked at 61,870 mt in 1969 (when the lake's fish biomass peaked) and dropped to an estimated 39,000 mt in 1970, to approximately 37,000 mt in 1971. A continuation in the decline in 1972 was probable. Reduced floods during 1970, 1971, and 1972 may have caused reduced catches, as a consequence of fewer nutrient inputs and clearer water. The latter condition results in greater transparency and poorer catches from multifilament nets. *Tilapia*

constituted about half of the catch in 1971, while other important species were Lates, Alestes, and Labeo.

There are presently no total indicators of fish production from the whole lake, and there is presently no feasible method for assessing the absolute abundance or production of the biomass of pelagic fish. In addressing the question of potential productivity of the lake, Reynolds made tentative projections of trends in species abundance and reviewed a number of methods for computing total production. He sees a pattern of increases in both the north and south reaches of the lake in primary consumers (Labeo, Distichodus, Tilapia), the increasing inshore dominance of bagrids (Chrysichthys spp.) in the south, and the dominance in open waters of the south lake by Pellonula and its predator Lates. Reynolds refers to Ryder's morpho-edaphic index of productivity, based upon dissolved solids and mean depth, to make a rough calculation of the lake's potential. This index indicates a sustainable yield of 40,000 mt per year, or 35-40 kg/ha. The validity of this calculation is corroborated to some extent by results of a similar estimate made of Lake Kainji's productivity. There, results using Ryder's index corresponded closely with the lower range of productivity computed by different methods. On Lake Volta, the yearly production potential as indicated by Ryder's morpho-edaphic index suggests that catch is close to total present production, and that small increases in fishing intensity could deplete present stocks. Increase in productivity by fertilization was judged by Reynolds to be out of

the question economically, and could have the disadvantage of encouraging the growth of more undesirable water weeds such as Pistia. However, it should be worthwhile to investigate the potential of converting shallows to fish ponds, and to experiment with bundles of brush or reeds as food surfaces and refugia.

Water Supply and Sewage

The Volta Lake can be described as a single environmental resource capable of providing a number of resource services: for example, hydropower, fisheries, and water for irrigation, industry and household needs. The exploitation of these resource services must take into account net benefits from various use levels of each, trade-offs and other interactions, and the limited supply of capital and human resources required to plan, implement, and manage the various uses. Boland postulates an optimal pattern of use, which would guarantee present and future combinations of various uses that are more satisfactory than alternate patterns. This optimal water resource management pattern requires a statement of the societal goals for managing the resource, which must take into account desired benefits as well as constraints on the attainment of these benefits. A formal articulation of the optimization, or maximization, problem will permit an analysis of proposed uses, which takes into account all relevant factors. This exercise is the essence of multiple-purpose resource planning and management.

A review of the various studies undertaken preparatory to the construction of the Volta Dam indicates an initial single purpose focus (general electricity to process bauxite), then a multiple-purpose focus (Halcrow & Associates 1951 report), and a return to the single purpose hydropower orientation (the 1959 Kaiser Reassessment Study). With the creation of the Volta River Authority there has been increasing recognition and research on the various other uses of the reservoir and its water supply. Dr. Boland discusses the various other uses that could be made of the water in the lake, which he terms water supply services.

Water supply can be obtained from the tributary streams, from the lake proper, and from the river below the dam, depending largely upon distance to the user, but also upon elevation and reliability of supply. The elevation factor raises the issue of whether or not it is desirable to pump water from the river to the Accra plains. Because pumping would use a portion of the electricity generated by the dam, it would thus compete with the use of reservoir water for the purpose of supplying electricity to the Tema industrial complex, even though no water is withdrawn from the reservoir. If water taken at Akosombo were lifted 70 meters in order to irrigate the Accra plains, 1.2 gallons would have to be released from the dam for every one gallon lifted by pump. The approximate break-even point would be a 60-meter lift. In simple terms, this would be the equivalent of taking water from the reservoir rather than from the river.

Withdrawals from tributaries of the lake would also compete with the generation of electricity. Tributary water is now being withdrawn at 19 points, and five more are proposed. No information exists, however, on the present and future quantities of tributary withdrawals, either in Ghana or in the upper watershed republics of Mali, Upper Volta, Togo, Dahomey, and Ivory Coast. Although quantities withdrawn at present in Ghana are likely to be small, this factor should not be ignored in development plans for the basin's water resources.

The water supply of the lake itself is of potential importance mainly to the estimated 100,000 persons who live in approximately 1,000 communities on or near the shores of the lake. Most of these communities, which include resettlement communities, do not appear to have an adequate community water supply, and for most it can be assumed that water is carried from the lake. This is undoubtedly an important factor in human exposure to schistosomiasis cercariae. Inoperative well pumps observed in several resettlement villages evidenced the apparent absence of institutional capabilities for maintaining installed equipment. Either local Councils or the Ghana Water and Sewerage Corporation are responsible for the pumps and wells. The Councils clearly lack the needed manpower and money, while the Corporation has experienced logistical problems in getting to the villages in order to maintain pumps.

In addition to the schistosomiasis exposure hazard, the use of lake water carries the hazard of bacterial contamination and the lesser problem of turbidity. These problems could be overcome, but prevailing conditions do not confer any advantage to the lake water supply if groundwater is available.

Given the nature of water use by lakeside communities at present, wastewater is not a significant factor in the lake's water quality. Even if standards of living and water consumption increased, it is doubtful how much of the proportional increase in wastewater would reach the lake.

Withdrawal of water from the lake for irrigation of the Accra Plains or other major use raises considerations of multiple use management. Planned hydropower capacity could use virtually all of the lake's annual inflow, but proposals for other uses of the reservoir water can be expected to appear. Two policy alternatives can be considered: prohibit withdrawals if these compete with electricity generation, or permit certain withdrawals even at the cost of foregone energy production. The second alternative would be followed if in the analysis the net social benefit from the water use exceeded the opportunity cost of foregone power generation.

Elaborate mathematical models and good data will be needed to fully evaluate proposals for competing uses. Up to the present time, it has not been necessary for any agency concerned with the Volta Lake to study the future demands for its resource services, except in a superficial way. But significant

withdrawals for irrigation purposes would surely compete with power generation water needs, and a multi-purpose management framework would be needed to guide evaluation methods.

Similar comprehensive evaluations will be needed for future demands on the lake's water by Accra and Tema. In those centers high rates of water consumption coupled with growth in population and industry are likely to lead to suggestions for major withdrawals from the Volta River or Lake. As opposed to irrigation demand, however, drinking and industrial water demands do not have pronounced seasonal peaks. These centers could be supplied by river water pumped from points below the dam; some of Accra's water is already being supplied in this way from Kpong. Cost of pumping was not reviewed, but it may compare favorably with the construction costs of conduits from intakes on the lake. Additional major withdrawals from the lake or below the dam should be considered within the context of a multi-purpose management approach to the water resource.

The assimilative capacity of the lake for wastewaters with organic content is great. The lake's volume has a vast dilution potential and given the relatively low productive status of the water, organic wastes could enhance productivity, although not without the possible water weed problems mentioned above in the assessment of artificial fertilization. Wastewaters will enter the lake at specific locations and wastewater assimilation is essentially a local phenomenon. Although villages were not observed to be important sources of wastewaters entering

the lake, at ferry crossing points where many people wait, human wastes are likely to be deposited in or near the water. Most important, urination into the lake ensures the perpetuation of the urinary schistosomiasis cycle.

Agricultural and industrial wastewaters are currently not problems. Use of certain persistent insecticides and herbicides in drawdown zone agriculture could, however, cause serious damage to sensitive fish and other aquatic life important to fisheries. Boland cites a hypothetical example in which industrial wastewater pollution is tolerated, at the sacrifice of reduced fish catch. He points out that the fisherman is essentially subsidizing the industry by giving up a portion of his catch so that the discharge may continue.

As long as demands for competitive uses of the lake's water and other resources are likely to occur, the Volta River Authority cannot escape the requirement for multiple-purpose management. Further, the lake cannot be effectively managed independent of its tributary streams and the river below the dam. Boland therefore recommends the formulation of a comprehensive river basin plan, and adds that all the nation's water resources should be subject to comprehensive multiple-purpose planning and management.

Biological Control of Schistosomiasis and Other Important Diseases

A review was made of the biological control aspects and control possibilities of river blindness (Onchocerciasis), malaria, sleeping sickness (Trypanosomiasis), and Schistosomiasis.

The black fly, *Simulium damnosum*, is the vector of the parasitic worm, *Onchocerca volvulus*, which causes blindness in advanced stages of infestation. While the lake destroyed much of the rocky, well-aerated river water habitat required by the fly for breeding, new habitats were created below the dam as water level dropped, especially at Kpong where rapids have resulted from diminished flow. Present control concentrates on the larvae of the fly during breeding season, by means of introducing DDT at low concentrations (0.1 to 0.3 ppm) into the river water. Natural enemies of the black fly have been discovered but not yet studied for their biological control potential. Caddis flies (*Cheumatopsyche obligitari*) prey on *Simulium* larvae; adult *Simulium* ovaries are attacked by a fungus (*Coelomomyces*) and a parasitic larval mite.

Malaria is hyperendemic in Ghana and the mosquito vectors breed on Volta Lake. The natural enemies of malarial mosquito vectors (*Anopheles gambienese* and *Aedes popiens fatigans*) include dragon flies (Odonata), aquatic insects such as corixids, motonectids, belostomatids and beetle larvae, and undoubtedly some native fish. These organisms have not yet been researched for their bio-control values, however.

The dam flooded large areas of the forest habitat of the tsetse fly vectors of sleeping sickness. While prospects for biological control are very limited by lack of knowledge of natural enemies, clearing of vegetation is effective in local reduction of vector populations. However, movement of people on the lake could expose them to local foci of tsetse populations.

Several biological control possibilities exist for urinary schistosomiasis, the most prevalent parasitic disease of the Volta Lake Basin, and an important disease outside the basin. Prevalence rates commonly reach 75 percent in villages on or near the lake. Exposure to infestation is high, especially for fishermen who dive to set nets as well as people who draw water from the lake. They are commonly children.

Biological control could focus on the vector snail habitat, the snails, ther cercariae, the miracidia, and intra-molluscan stages. No effective control has been devised for the submerged Ceratophyllum weed, in which the Bulinus snail vector is found in most abundance. This is now a dominant submerged weed of the lake. The snails are known to be preyed upon by the puffer fish (Tetraodon sp.) which lives in Ceratophyllum beds, and possibly by water fowl. It has been observed that in villages on the lake with domestic ducks, there are low populations of snails. Both these predators deserve serious consideration as control agents. To a slight extent Bulinus snails are also attacked by young Lates, Alestes barmose, Physailia, and Synodontis spp.

Larvae of the Sciomyzidae flies are known to prey upon snails. Laboratory and field studies are being pursued in other countries for their use as control agents of snail intermediate hosts. However, the foreshore habitat conditions of sites visited in the south Volta Lake were not suitable for sciomyzid flies, which generally cannot survive a drastic seasonal decline in water level. Further work on the life cycles of as yet unknown sciomyzid species could turn up species adapted to such conditions.

Two species of predaceous and competitor snails have been considered for the Volta Lake. Only snails exotic to Ghana are known, however, and the introduction of one, Marisa cornuarietis, was rejected since it could become a serious pest of rice.

Several invertebrates, including oligochaete worms, mosquitoes, and Hydrozoa, are known to kill schistosome cercariae and miracidia. The detailed ecology of these organisms is unknown, however, and nothing is known of their impact on transmission of schistosomiasis. Guppies (Lebistes reticulatus) are known to feed voraciously on cercariae, and quantitative laboratory and field studies have shown that they have a significant effect on transmission rates.

Within the snail, there exists the possibility of biological control with non-disease producting trematode larvae which could be antagonistic to the schistosome at the redial stages, by dominance, by predation, or by indirect antagonism. The mechanisms

of indirect antagonism are not clearly known. Lastly, non-disease producing trematodes may be used to shorten the life of the snail or to reduce its fecundity by parasitic castration.

PART II

SURVEY OF THE VOLTA LAKE AND CERTAIN ENVIRONMENTAL IMPACTS

1. Introduction

Large dams, and especially large dams in the tropical latitudes, have been receiving increasing scrutiny and attention from many quarters. For developing countries poorly endowed with fossil fuels, the hydropower potentials of their river systems are the only major autonomous source of fuel. Further, hydroelectric power is clean and its perpetual production is only limited by climatic variability and sedimentation. Both limitations can be countered to a great extent with adequate design and management. The projected world shortages of fossil fuels relative to demand and the embryonic state of alternative technologies for producing energy have immeasurably increased the value of hydropower potentials in all nations, but particularly in those which are developing an industrial base.

Dams are not without costs, however. They have drowned forever remains of ancient civilizations, rich alluvial soils, forests, and human communities. They interrupt the biology and hydrology of running water systems, to the detriment especially of fish whose life cycle is spent both in the river and in the

ocean. The large man-made lakes which form behind dams produce benefits, but also costs, associated with their limnology and the human uses made of their resources.

Dams are a type of infrastructural investment that typically requires international financial and technical assistance. International development agencies such as the World Bank, FAO, and USAID have become increasingly concerned with the environmental impacts and costs associated with these engineering works, and are evolving guidelines designed to obtain accurate assessments of these various costs. Also, developing nations are not unaware of the potential environmental costs and management problems of tropical dams and man-made lakes. It is clearly to their benefit to anticipate all possible costs as well as benefits in order to obtain realistic economic and financial apprasials and develop adequate management and research programs. A review of the experiences of African dams within this context represents a valuable opportunity, and it is made possible by the substantial amount of published studies and research.

Perhaps the greatest body of information on tropical dams and man-made lakes centers on the African continent. The experiences of these dams is of inestimable value for future tropical dams and man-made lakes. Fortunately, much of this experience has been recorded and a very considerable body of scientific and socio-economic literature has accumulated in various compendia, publications on research in various aspects of hydrobiology, or in pre-investment studies. Until recently,

this information has been widely scattered and sometimes of difficult access, and generally in a form that is difficult to use.

The Volta Lake, the largest man-made lake in the world, has been comparatively well studied. Since its creation in 1964 with the closing of the dam, it has passed through the phase of ecological instability to become by 1973 a relatively stable body of water. What happened to the lake's limnology, fisheries, and aquatic plants during this nine-year period represents a valuable experience that should be carefully studied by planners who are considering new dams in Africa and elsewhere in the tropical world.

The Volta River Project

Background.--As early as 1915, the use of hydropower to produce aluminium in Ghana was envisioned. This potential was investigated in a number of studies, but the chain of events leading to construction of the dam began only after Ghana achieved independence in 1957. A definitive assessment of the hydropower scheme was made in 1959 by Kaiser Engineers, and thereafter international financing was arranged. In 1961, the Volta River Authority (VRA) was established to carry out construction and administration of the dam. Reponsibilities of the VRA later expanded to include resettlement, and research on the lake's fisheries and limnology, public health, and agriculture, including social and economic aspects.

The lake.--The Volta Lake is dendritic in shape and has a shoreline of approximately 6,400 kilometers. Its 8,500 square kilometer surface makes it the largest man-made lake in Africa. The lake's maximum depth is 905 meters, and its level varies by 3 to 3.5 meters, exposing at low water an average of 800 square kilometers. The climate of the lake--and the rest of Ghana--is under the influence of the dry, northerly harmattan winds, during November to February, and during the rest of the year, the cool, moist air masses moving inland from the Atlantic. Precipitation shows a diminishing gradient from north to south, with a corresponding variation in vegetation from evergreen forests near Akosombo to a savannah woodland in the north.

The dam.--Construction of the Akosombo dam began in 1962, after several decades of preparatory studies, and following lengthy negotiations for its financing. The financial viability of the project was ensured by a 30 year contract to sell electricity to the Valco aluminium smelter, which was constructed in Tema on the coast. The initial cost of the dam and power plant was $196 million and the smelter investment amounted to $128 million. The smelter was financed principally by Kaiser Aluminum; the Reynolds Metals Company contributed 10 percent. The International Bank for Reconstruction and Development, the government of England, and the U.S. Government (AID and the Export Import Bank) lent

funds to construct the dam. Part of the loans were applied to resettlement costs, transportation systems and the fishing industry.

Final installed hydropower capacity at Akosombo will be approximately 830 megawatts. By 1973, capacity had reached 768 megawatts and total power produced in 1973 was MG. Additional loans have been negotiated with the IBRD to increase generating capacity, and the Canadian government has lent money to build transmission lines to Togo and Dahomey, who now purchase a portion of the power. Most of the power goes to Valco and the Electricity Corporation of Ghana. A textile plant near Akosombo consumes a small proportion of the total output.

Resettlement.--Because 80,000 persons had to be relocated, resettlement was a major undertaking and a major financial cost. It was estimated that the total cost by 1971 would amount to approximately $34 million (at US$1.00 equals N¢1.02) in 1969 dollars. Resettlement housing and roads were major cost items, approximately $13 million and $3.0 million respectively, as of 1968. Resettlement was preceded by well designed and executed socio-economic studies. Land clearing was delayed, however, partly owing to delays and uncertainties in the project's financing. By 1964, only 8,000 acres of the targeted 54,000 had been cleared. The procurement of tractors for mechanized cultivation--a necessary input for the modern farming envisioned--was also delayed.

When the lake filled in 1968, four years after closure, 25,000 of the 67,000 resettled persons (some 13,000 opted for cash compensation) still resided in the 52 established villages. Slightly more than half of these had land to work. One-third of the tractors were unserviceable. The annual value of agricultural production had returned only $3 out of every $8 invested by the government. Pumps for community water supply also became unserviceable, and people in villages near the lake began to draw water from the lake, thereby increasing exposure to schistosomiasis infection. Since the potential benefits of the lake's fisheries had not been integrated into the resettlement village planning, the large fish harvests which peaked at 60,000 m.t. in 1969, did not significantly contribute to the economic base of these villages (Lawson, 1968). Rather, the benefits were realized by itinerant fishermen, mostly Ewes from the region and the Lower Volta, who dwelled in spontaneously constructed fishing villages along the shore. Also, the mechanized farming approach in the resettlement villages had not achieved original expectations (Afriyie, 1970), and emphasis has since shifted to a Land Clearing Project assisted by the World Food Programme in which payment is in food rather than in cash.

Research and Studies on the Lake and its Environment.--There was early concern for the public health, resettlement and inundation impacts of the Volta Lake project. The first

social surveys focussing on resettlement were made in 1962. Other research on the lake was first organized, in 1963, under the Volta Basin Research Project in the University of Ghana, and focussed on archeology in the basin as well as the terrestrial and riverine biota and ecology and, later, the lake's hydrobiology. During 1963 to 1970 sixty publications and thirty-six technical reports resulted from this effort. In 1968 research was expanded with the creation of the Volta Lake Research Project headquartered in Akosombo and jointly sponsored by the UNDP and the government of Ghana. This was a three-year program focussed on research in fisheries, hydrobiology, public health and resettlement. UNDP support of this project ended in 1972, although the project still continues, with increasing emphasis on drawdown agriculture and fisheries. In 1972, WHO initiated a separate research project on schistosomiasis control on the lake, as part of a special research program focussing on schistosomiasis in man-made lakes in Africa.

Objectives and methodology of the present study

Previous and on-going research was taken into account in the definition of the objectives of the present study. This was done in 1971 in consultation with Volta River Authority scientists and other Ghanaian scientists. A major consideration was that the Smithsonian Institution

study would complement work being carried out by other organizations, including the Volta Lake Research Project.

The general objective of the present study was to develop a comprehensive documentation of the various environmental impacts--both beneficial and negative--of the impoundment of the Volta River, in order to derive from this experience guidelines for other tropical reservoir projects. These guidelines would aim to orient such projects so as to anticipate, assess, and provide for all possible impacts. Several kinds of impacts had already been well studied in connection with the Volta Lake Project, notably resettlement.* This aspect was therefore not reviewed.

After considering the complementarity of existing and on-going research to the general objectives of the Smithsonian Institution's study, the following study agenda was developed:

> Lake geology - building on existing information, a report will be written on the geological formation of the lake basin. Emphasis will be given to the types of outcrops and the geological significance of such features.

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*Comprehensive treatments can be found in The Volta Resettlement Experience (Robert Chambers, editor, Praeger, New York and London, 1970); and in "Volta Lake in Relation to the Human Population and Some Issues in Economics and Management" by E.A.K. Kalitsi (in Ackermann, White and Worthington, editors, Man-made Lakes: their problems and environmental effects, American Geophysical Union, Washington, D.C., 1973).

Groundwater geology and related hydrology - emphasis will be placed on the possible sources of ground and surface water to the lake and any probable interchange of water between source and the reservoir. Attention will be paid to evaporation as related to surface area and surface cover of the lake.

Biological control - using existing knowledge of the epidemiological and public health aspects of schistosomiasis and other waterborne diseases, attention will be paid to the interactions of plants, animals and diseases to determine the alternative feasibilities of methods of natural control of the organisms.

Water supply and sewage - using available Public Health and Urban planning documentation and direct observations an evaluation will be made of the current flow, water storage capacity and multiple use potential of lake water in support of small and large human settlements. The absorptive capacity of the lake in handling pollutants will be estimated.

Mineral cycling - measurements of water chemistry and estimates of mineral sources and biological utilization of various minerals will be evaluated in terms of the net turnover of minerals in the lake.

Fish nutrition and production - an evaluation will be undertaken of the requirements of commercial species for nutrients and their potential production in relation to present and projected nutrient flows. Attention will be paid to the potential role of fertilizers in changing the rate of fish production.

Evaluation of aquatic plants - an attempt will be made to evaluate the competitive success of the various plant species and their contribution to and withdrawal of nutrients and to project alternative estimates of their role and control in the lake.

Evaluation of plankton - from existing data on plankton occurrence and fluctuations and knowledge of food habits of fishes and their potential role in water usage, an analysis will be made of the need to stimulate growth or to regulate its abundance.

Lake topographic survey - if possible, a preliminary bathymetric chart will be developed to show the depth contours of the lake or of its important channels.

Scientists from the United States were selected, in consultation with the VRA, and undertook two to four week visits in 1973 to meet with Ghanaian scientists, review work done, and carry out field observations. Prior to these field visits, a comprehensive annotated bibliography on the lake's hydrobiology was prepared as a reference document (Appendix 3). Their reports, some of which were drafted in Ghana, constitute the basis of the present document.

2. Lake Geology and Groundwater Hydrology

A brief review of existing publications, maps and other materials and a visit to the southern lake were undertaken for the purpose of assessing the geologic environment of the Volta Lake, and of examining possible sources of ground and surface water to the lake and any probable interchange of water between source and the reservoir. The balance between precipitation over the reservoir and evaporation from it was evaluated.

The Geologic Environment of Volta Lake

The geologic environment of Volta Lake is described in several publications of the Ghana Geological Survey Department (Junner and Hirst, 1946; Tevendale, 1957; Annan-Yorke and Cudjoe, 1971), and is summarized briefly as follows:

Volta Lake lies in a sedimentary basin that extends over two-fifths of the area of Ghana. The sediments within this basin--named the Voltaian Formation--are in horizontal or gently dipping beds; they are known to be more than 700 meters (2,300 feet) thick (in a borehole at Tamale) and may be as much as 2,600 meters (8,230 feet) thick west of the Oti River. The formation is believed to have been deposited early in the Paleozoic Era 400 to 600 million years ago; no fossils have been found, so that more accurate dating is not possible.

The upper part of the Voltaian Formation is made up of sandstone 300 to 400 meters (960 to 1,280 feet) thick, with

massive beds at the top and thinner platy beds below. These sandstones form escarpments along the northern and western rims of the basin, which however have been cut away by the White Volta and Black Volta Rivers. Along the south rim of the sedimentary basin these sandstones form a higher escarpment (the "Southern Highlands") which constitutes the topographic divide between the basin of the Volta River and those of the Pra and Tano Rivers and other coastal streams. Generally the Upper Voltaian sandstones form the topographic highs in the sedimentary basin, and are more than 300 meters (960 feet) above sea level in extensive areas.

The middle and lower parts of the Voltaian Formation are the surficial rocks in the low lands (generally less than 150 meters above sea level) within the sedimentary basin. These include shale, mudstone, siltstone, arkose, sandstone and conglomerate, some of which are named for towns or rivers near outcrops that have been described (such as Obosum beds, Afram shale, Sang conglomerate, Oti beds, Akroso conglomerate). However, outcrops are few: generally these sedimentary rocks have been long and deeply weathered and are now completely decomposed to depths of many feet, leaving red clay and sand, and laterite in extensive areas.

Surrounding the Voltaian sedimentary basin, and underlying it, are pre-Cambrian rocks which range in age from 600 million to billions of years. These are crystalline rocks, with granites at the surface over extensive areas both in northwest and

southwest Ghana, and metamorphosed sediments and lavas in even more extensive areas. The youngest of these ancient metamorphosed sediments appear to be rocks of greatest economic value in Ghana. The Tarkwaian Formation, outcropping in a belt extending from the Southern Highlands near Konongo southeastward past Tarkwa, has been a major source of gold and manganese (Hirst, 1938, 1962). The Togo Formation includes the quartzite that outcrops at Akosombo Dam, and the intensely folded and metamorphosed rocks that form the Akwapim Range (southwest of the Volta River) and the Togo Range extending northeast to the Togo border and thence north to form the "Eastern Highlands."

Effect of Volta Lake upon the Geologic Environment

At its maximum controlled elevation--276 feet above sea-level--Volta Lake inundates about 8,500 km^2 (3,275 mi^2) or about eight percent of the Voltaian sedimentary basin. Very few mineral resources are known to have been inundated, and they were of limited economic value: limestone in the bed of Afram River, suitable for the manufacture of cement; limestone on the eastern flank of the Volta Gorge at the Mem Rapids, suitable for agricultural use (Mitchell, 1960); sands and gravels along the Volta River and its tributaries, which have yielded isolated diamonds from time to time.

Volta Lake has also inundated the floodplains of the Volta River and its major tributaries. Doubtless some valuable agricultural land was lost. But the lake required resettlement

of only 80,000 people (about 10 per km^2 or 25 per mi^2 of inundated area), whereas the average density of population throughout Ghana in 1960 was 30 per km^2 or 75 per mi^2. Thus the pre-lake riverine area was evidently supporting less than its share of the population. The area of the sedimentary basin is still the least populated in Ghana, with extensive areas containing fewer than 10 per km^2 (or 25 per mi^2).

In the rising water of Volta Lake many trees and shrubs have been submerged, including extensive areas of woodland and even forest. According to Addo-Ashong (1969), the submerged wood is likely to be preserved for many years, and the large trees with more heartwood will last longer. The rate of deterioration will depend upon durability of the wood. These submerged trees unless physically removed become hazards to shipping, boating, fishing, and studies of sediment.

The two most important impacts on the geologic environment are related to sedimentation and seismic effects of the lake's mass. Neither is well studied, however, so their magnitude and importance can only be speculated upon.

Reservoir sedimentation.--The waters of the Volta and its tributaries are generally muddy and sediment laden. Naturally the river transported sand and gravel through the Volta Gorge, which might rest temporarily in bars and islands, and be covered by several centimeters of clay and silt during declining stages of the river. The sediment is now accumulating in Volta Lake at rates that are not known or even estimated. The volume

of the lake is so great that the sediment accumulation is not a serious problem. The Geological Survey Department proposes to measure the suspended sediment carried by principal tributaries (Barning and Banson, 1969, p. 86), but this should be done as an extension of the stream-gaging program, coordinating sediment-samplers and current-meters to determine both the histogram of suspended sediment and the daily annual flow of water and sediment. Existing gaging stations (Oti River at Saboba, Black Volta at Bamboi, White Volta at Yapei, Pru River at Prang or Pruso, Afram River at Aframso) may be satisfactory for sediment-gaging, and if so the data may be correlated eventually with river discharge to provide estimates of the sediment transport since filling of the lake.

A complete record of sediment inflow will not, however, answer the question of where has the sediment been accumulating in the past nine years, and where is it likely to go in the future? A similar question concerning Lake Mead on the Colorado River in southwestern U.S.A. led to a comprehensive survey 14 years after the reservoir began filling. The survey included echo-sounding techniques, with some transducers that obtained reflections from the top of the reservoir sediment and some that penetrated the thin muds and obtained reflections from more solid stuff below. The total accumulation, about two thousand million tons, checked closely the aggregate quantity of suspended sediment passing the Grand Canyon gaging station

upstream from the reservoir. The sediment formed a delta in the artificial lake, with bottomset beds of silt and clay extending along the lowest part of the reservoir to the dam, where the clay was more than 30 meters (100 feet) thick; foreset beds of sand that were formed by the river as it entered the lake; and horizontal topset beds that covered the forests when the lake was at highest stage.

Seismic effects.--The creation of the lake has added weight to the underlying rocks, amounting to 165 million metric tons when the lake reaches its estimated capacity of 165 km^3, and fluctuating through a range of 25 thousand million tons during normal fluctuations of lake level at Akosombo Dam. The significance of this is not known since the necessary seismic measurements were not made during lake filling.

History indicates that most of Ghana is stable seismically, but the triangle extending southeastward from the Togo quartzite--or roughly from a line joining the cities of Accra and Ho--is earthquake country. Disastrous earthquakes occurred in Accra in 1862, 1906, and 1939, and the 1906 shock was even more severe at Ho. In the century before Akosombo Dam was built, minor tremors occurred in 1883, 1907, 1911, 1918, 1923, 1925, 1930, 1933, 1935, and 1942.

Three earthquakes of intensity 5 on the Modified Mercalli scale are reported (Kumi, 1973) since filling of the Volta Lake began in May 1964. The first occurred in November 1964 when 28 km^3 of water had been impounded; eleven countries recorded the

tremor and placed its epicenter near Koforidua, about 40 km south of the reservoir. Another earthquake occurred in December 1966 when the reservoir contained 102 km^3, and a third occurred in February 1969 with storage at 162 km^3, but the epicenters for these shocks were offshore from Accra and more remote from the reservoir. Unfortunately, there has been no instrumentation that might indicate the stress of this increasing load upon the earth's surface, or the earth's reaction to the stress. The Geological Survey Department proposes (Barning and Banson, 1969, p. 88) to record micro-earthquake activity around Volta Lake by portable seismometers of high sensitivity, and hopes that micro-earthquake research eventually may be helpful in predicting the occurrence of larger events.

The earthquake-triggering effects of change in pressure, changes in weight, vibrations, etc. are of great interest to people in all earthquake prone parts of the earth. Instrumentation to measure the effect of Volta Lake upon seismic activity might therefore deserve and receive support from international organizations such as UNESCO and from scientific institutions in many nations. Also, Ghana might well obtain co-sponsorship of such a scientific project from neighbors along the Atlantic Coast and in the Volta River Basin.

The Hydrologic Environment of Volta Lake

This section is intended to emphasize groundwater as it might affect Volta Lake or be affected by it. The treatment

of this subject is limited, however, by the lack of data concerning the groundwater beneath the lake, and of syntheses or analyses that might relate the lake to the occurrence or movement of quality of groundwater. From the history of water resources development in Ghana (Lartey and Smith, 1968), it is evident that meager data, unreliable data, or no data are chronic complaints in all fields of water development, including water supply, irrigation and drainage, water power, flood control, water transportation, and groundwater. This section is therefore organized to summarize several phases of the hydrologic cycle as they affect Volta Lake or are modified by it. A discussion of groundwater as a separate resource is presented.

Precipitation inflow vs. evaporation outflow.--Six stations near Volta Lake, all in localities where average annual rainfall is 1,400 to 1,500 millimeters (55 to 60 inches), provide records of pan evaporation ranging from 1,450 to 1,700 mm annually (57 to 70 inches). The evaporation rate from pans is characteristically greater than that from large reservoirs, and a correction factor is commonly applied. For Volta Lake only a small correction would make the inflow from rainfall equal to the outflow by evaporation. The data available in Ghana indicate that loss by evaporation (from the lake surface) is nearly balanced by gain due to rainfall upon that surface.

Possible climate change caused by Volta Lake.--Theoretically, the creation of the Volta Lake would increase atmospheric moisture by making more water available for evaporation. To check on the possible effect of the lake upon rainfall, Amissah (1969) made statistical analyses of data from four rainfall stations--Accra, Akuse, Kete Krachi, and Tamale--and could find no conclusive evidence that monthly rainfall at those stations has changed since the creation of the lake. However, comparison of monthly run-off of Volta River before and after the lake was created (Kumi, 1973) indicates some change in run-off pattern, with a greater proportion occurring in August and September, and less in October. However, since 1964, the monthly run-off has been calculated from the monthly outflow from the dam, plus or minus any changes in storage in Volta Lake. Its reliability therefore depends upon the accuracy of the gage-height, storage-capacity curve. Storage changes comprised a large part of the calculated river flow in years prior to 1968, while the lake was filling. As Amissah suggests, several more years of data will need to be studied before definite statements can be made as to climatic changes caused by the lake.

Surface inflow to and outflow from the lake.--A summary of the water resources of Ghana (Krishnamurthy, 1964) provides tabulations of average annual run-off of the Volta River and its major tributaries as well as of other rivers in Ghana. One tabulation of monthly and annual run-off shows that the Volta River

at Senchi (before Akosombo Dam was constructed) ranged from 13 km^3 in 1958 to 91 km^3 in 1963; also that the run-off in 1963 was greater than the total run-off in the three years 1958 to 1960. In 28 years the recorded run-off was within 10 percent of the mean in only three years, but it was more than 25 percent below the mean in eight years and 25 percent above the mean in eight other years. It is important to know about the deviations from the mean, because they cause problems and even crises in water management.

In practically every aspect of water-resource development, the government and its consultants have long been handicapped by lack of streamflow data. Interest in the Volta Basin development led to a decision in 1954 to start hydrologic observations on a continuing basis, but this decision was not implemented until 1959. Streamflow records were published in water yearbooks for the years 1961 to 1967 by Hydrologic Services (Ghana Public Works Department), but these were limited to gage heights and instantaneous discharge measurements. Data have now accumulated for another five years, and there are plans to use rating curves to calculate average daily discharge, and to publish monthly and annual run-off totals also.

After the urgency of data for operations and management has passed, the daily details of streamflow have no more interest than old daily newspapers. For historical studies, run-off records are most convenient if compiled and tabulated by months and years, and several countries are now publishing tabulations

of streamflow data that may cover 25 to 50 years of record on a single page. An experienced hydrographer, with collaboration and assistance of Ghanaian stream gaging staff, could doubtless derive the desired run-off totals from existing data in Ghana, perhaps by computer programming.

Subsurface inflow to and outflow from the lake.--Unfortunately, there are no observation wells in Ghana--no records of water-level fluctuations, or of the effects of pumping in the pumped well or in adjacent wells, or of progressive lowering of water table by pumping, or of wells whose yield is sustained year after year by recharge. Specifically, in the Voltaian sedimentary basin during the filling of Volta Lake there are no records of water levels in wells near the lake to show whether those levels were affected by the progressively increasing volume of water in the lake. Of course, the areas that are inundated by the lake during high stages and then re-emerge as the lake level recedes, have been subjected to infiltration and percolation of the water into soil, subsoil, and underlying rock material wherever pore space is available. This subsurface water becomes of critical value to drawdown agriculture whenever the roots of cultivated crops can reach it and sustain the plants. But the extent of the lake's influence upon groundwater is not known.

Each new dam and reservoir presents an opportunity to measure the effect of surface impoundment upon groundwater. As an example, a dam is planned at Weija on the Densu River, to

provide municipal water and some irrigation in western suburbs of Accra. The Densu Basin is being instrumented for water balance studies (Water Resources Research Unit, 1971). Periodic measurements of water level in any wells in the vicinity of the proposed reservoir would provide data as to natural conditions. Drilling of additional boreholes at suitable locations would provide data on groundwater during the period the surface reservoir is filling. These wells could also be pumped to provide water supply to communities that will ultimately depend upon the lake, until the lake and distribution system are ready to serve them.

The groundwater resource.--Metamorphic rocks, granites, shales, and mudstones are among the most impermeable rocks on earth. They are also the rocks underlying most of Ghana. It is fortunate that they are so ancient because there has been long enough time for jointing, fracturing, and deep weathering of these rocks, which thus gain a variable but low secondary permeability. Water that saturates these pores becomes groundwater, which is encountered in boreholes and may be withdrawn for use.

The Nathan Consortium (1970) summarized the groundwater potential after testing the yields of about 1,200 boreholes. Crystalline rocks decompose to sand and clay with low permeability down to a depth of nearly 25 meters (75 feet). Boreholes should penetrate 10 to 15 meters into the weathered rock beneath this sand and clay, and thus to a total depth averaging 35 meters (110 feet). Ninety percent of the wells thus constructed will

provide enough water for a hand pump. If the wells penetrate all the weathered zone, to a probable depth of 60 meters (200 feet) or more, 50 percent will have yields sufficient for a motor pump, and the probability could be increased to 75 percent by geological and geophysical exploration. Sedimentary rocks are completely decomposed to depths averaging about 10 meters; boreholes in the sedimentary rocks have generally lower yields and higher failures, but geological and geophysical exploration can improve to 60 percent probability of a yield sufficient for a motor pump.

Groundwater development.--In their analysis of water-resource development and planning in Ghana, Lartey and Smith (1968) consider groundwater only as a source of rural water supply, where it has a very essential role. In 1960 there were 37 urban communities (population 10,000 or more) with aggregate population of 1,145,000. The rest of the population--5,582,000 or 83 percent of the total--lived in about 30,000 rural communities. About five million people (75 percent of the total population) lived in 9,800 localities with population between 100 and 9,999. Many of these communities are too remote from potable surface water or too small to justify piping a supply to them. These are the communities where a groundwater supply would be a blessing.

The present policy of the Ghana Water and Sewerage Corporation (Bannerman, 1972a) is that rural communities with population of 2,000 or more would have pipe-borne drinking water

supplies, whether from deep wells with motor pumps or from surface-water sources. For villages of 500 to 2,000, the corporation provides a village well equipped with hand pump. These have generally been called "shallow" wells, which is unfortunate if it results in abandonment of a hole after drilling only 30 or 35 meters (100 to 120 feet), because greater depth may yield enough to meed demand. Some boreholes must go as much as 300 meters to obtain sufficient supply even for a small village. About 1,200 boreholes had been tested for yield by 1969 (Table 1).

The data in Table 1 show that about 30 percent of the boreholes throughout Ghana have yields sufficient to justify a motor pump--2,000 imperial gallons per hour, or 40 U.S. gallons per minute. But even in this "most successful" group yields are low for municipal supply, and are hopelessly inadequate for irrigation as compared to other parts of the world. Some geologic formations do better than average: the younger rocks along the southeast and southwest coast, in very small areas; the Birrimian metamorphic rocks that underlie the southwest margin and include all the Upper Region. But the Voltaian sedimentary basin is poorer than average, especially in the Ashanti and northern regions; the Dahomeyan (beneath the Accra Plains) is worst of all. It is fortunate that those plains are in an area that can be irrigated by water from Volta Lake, although irrigation is likely to create problems too in such impermeable country.

TABLE 1. Borehole Test Data Throughout Ghana[a]

Geologic Unit		Boreholes			Yield of Boreholes %	
Name of Formation	Area of Ghana %	Number	Average Depth ft.	Failures	Hand-pump wells, 500-2000 gph	Motor pump wells, 2000 gph
Crystalline Rocks						
Granite	20	414	160	20	42	17
Togo quartzite, sandstone	1	80	240	31	30	29
Tarkwaian quartzite, phyllite	2	32	230	9	50	22
Birrimian metamorphic	27	259	200	10	38	45
Dahomeyan gneiss, schist	4	20	150	80	5	0
Summary:	54	805	200	19	38	28
Sedimentary Rocks						
Eocene-Cretaceous sandstone, limestone	1	103	350	22	15	52
Voltaian sandstone, shale	42	203	290	28	34	22
Buem shale, volcanics	3	94	220	12	42	39
Summary:	46	400	290	23	31	34
All Ghana:	100	1205	230	20[b]	36[c]	30[d]

[a]Source: Nathan Consortium, Ghana Sector Studies, 1970 Interim Report B, Occurrence of groundwater, p. 7, table 2.

[b]244 wells.

[c]434 wells.

[d]257 wells.

In the U.S.A. similar crystalline rocks, deeply weathered, are found in the Piedmont of the Appalachian Mountains, and North Carolina is the area to observe groundwater development for municipal and modest industrial use. The only other country having a similar groundwater province is South Africa. Robert Bannerman, hydrogeologist of GWSC in Kumasi, has visited North Carolina for groundwater studies under Ralph Heath, and he appears to be well qualified for the task of borehole development, and training of hydrogeologic assistants in Ghana (Bannerman *et al.*, 1972).

One field of expertise that may be of great value in selecting sites for productive boreholes has not yet been developed or imported into Ghana. Photogeologists can identify and interpret geologic formations and structures on the basis of aerial photographs of countries they have never seen. In Ghana, the occurrence of groundwater is related to such features as joints, fractures, folds, and shear zones, linear features that may be identifiable in aerial photos. Available aerial photos could be important tools in the groundwater development program.

Groundwater management.--In the broadest sense, water management includes all aspects of planning, exploitation, development, utilization, allocation, regulation, conservation, and protection of the water resources, presumably in the public interest and benefit. Groundwater management is an integral part of the total water resource. In comparison with the large rivers and abundant rainfall, and the huge reservoir formed by

Akosombo Dam, the groundwater resource of Ghana is practically microscopic and likely to be neglected in most water planning and management, even though it is vital to many people in extensive areas as the only potable and unpolluted water supply.

In the restricted sense of a single well, development is like the production of a new automobile or airplane which should be functioning properly in all respects when it is delivered to the user. For a borehole, development includes exploration and selection of site, drilling into water-bearing rocks, improving the yield by using screens and gravel pack and removing clay and silt particles, and installing a suitable pump and motor.

Thereafter comes the problem of upkeep, which includes careful operation, and proper maintenance of the pump and motor--and of the well. This is necessary to insure that water can be produced as needed without breakdowns or stoppages that can cause crises when water supplies fail. Efficient operation requires adequate inspection and monitoring of all the elements that contribute to the water production. Wells are designed and constructed to produce water at specific rates and at optimum efficiency, but yields may decrease and drawdowns increase in time, because of reduced efficiency of an aging pump or motor, or because of corrosion or encrustation of well casing and screen, or because of gradual accumulation of clay and silt, or slime produced by iron bacteria.

Declining yield may not be the fault of the well or its construction or equipment, but may instead result from inadequate recharge to the zone from which the well has been drawing water. In most areas in Ghana boreholes must pass through 10 to 15 meters (30 to 50 feet) of decomposed soil to reach weathered rock that is water-bearing. This decomposed soil is so impermeable as to prevent infiltration, and practically all the rain upon the land necessarily runs off. Thus, even though the average yield of a well in Ghana is quite low, it may be greater than the rate of replenishment, and the well therefore, in pumping water that has accumulated very slowly, depletes the storage progressively.

Ghana has so far neglected to monitor the effects upon the groundwater resource of pumping from boreholes. It was reported that in some wells which have been operating for several years, the water level is now perhaps five or six meters (16 to 20 feet) lower than when pumping was started. These reports were not substantiated with measurements, records, or identification of a specific well or specific locality.

The absence of basic data and the need for observing fluctuations in wells and monitoring the effects of pumping as well as of rainfall, flood run-off and drought, have been pointed out (Bannerman, 1972b). Especially where a rather large community obtains its water from several boreholes, an observation well suitably located could provide data as to whether the groundwater

is being depleted--and the forewarning may lead to timely planning for additional or supplemental or alternative supplies. In addition, water levels should be measured, perhaps monthly, in observation wells in a network planned to include various geologic formations and rates of rainfall and distances from rivers and lakes. Some boreholes would need to be drilled for the special scientific purpose, and some might be wells abandoned for one reason or another.

Groundwater research.--Although Ghana does not yet have a nationwide program of groundwater studies (involving a network of observation wells, records of water-level fluctuation, and various pump tests and aquifer tests) some research is in progress in groundwater hydrology (Water Resources Research Unit, 1971). This work, still in a pilot-project stage, is chiefly in the Accra Plains underlain by the Dahomeyan Formation, which is generally recognized as one of the least permeable in the country. On these plains, wells of small yield would be sufficient for cattle or other stock, or small gardens. So far, eight boreholes have been completed, with yields in the 600 to 1,500 gph range, good for the Dahomeyan, and perhaps enough for a small diversified farm. Natural vegetation patterns have been helpful in suggesting groundwater zones, although seismic and resistivity measurements are also important in site selection. Bailing tests are a very inexpensive method of determining the potential yield of the boreholes. In the solid rocks the holes

are well preserved without casing, also reducing the cost of producing water. The measurements of water levels in the wells will permit study of the form of the water table and of the fluctuations during the rainy season.

This research, and other geohydrologic studies and activities, are deserving of increased support and coordination if the full potential of groundwater is to be realized.

3. Lake Bathymetry and Related Surveys

Introduction

This section reports the results of bathymetric survey trials of the lake undertaken to test the adequacy of fathometric survey techniques for obtaining more accurate information on the bottom configuration of the reservoir. The need for better bathymetric data was related to the data requirements of area-capacity calculations, sedimentation estimates, navigational charts, and sub-bottom lithology important to seismic considerations and groundwater.

The findings and recommendations are based on the results of library and field investigations conducted at the Volta Lake Authority facilities at Accra and Akosombo, during the period May 4-16, 1973.

It is recognized that additional effort will be required to formulate detailed recommendations. However, it is believed that the comments and general programs recommended in the report are realistic and can be considered for implementation. Underlying some of the recommendations, with specific reference to the sedimentation program is the belief that developers of major works have an incumbent

responsibility to provide accurate documentation even though some facets of the data will be only of limited use during the lifetime of the current generation.

The comments and recommendations regarding bathymetric surveys are for immediate term benefit, and are based on a review of the source maps from which area-capacity data now used in reservoir operation were derived. It is concluded that this data may be inadequate for efficient water management, and recommendations are made to conduct a limited resurvey of the live storage foreshore so that current needs for accurate storage data can be fulfilled. The recommendations regarding sedimentation are directed toward long-term application, although some immediate applications are included. This section is generally confined to the measurement of deposited sediments, with the understanding that programs for measurement of stream discharge and velocities, and sediment loads are planned or being executed by others.

Current velocity and water temperature measurements are recommended, not only because they are useful in the study of deposited sediments, but also because they will be needed for the prediction of sedimentation and hydrobiological work. Finally, these data can be obtained conveniently during survey operations.

Comments and references regarding inundated vegetation were developed during investigation into the conditions that

may affect the accuracy and utility of sonic profiling. Ancillary benefits of the sonic profiling recommendations may extend to a technique for measuring and predicting the decay rate of vegetation inundated by tropical reservoirs.

Comments on navigation were made because of the obvious impact that sedimentation of inundated river channels may have upon the orderly operation, planning and maintenance of the navigation program. Owing to circumstances, the time spent on this was limited. Additional study to define problem areas should be made by, or in cooperation with, the Marine Operations Department of the Volta Lake River Authority.

Bathymetric Survey Trial

Approximately 150 feet of fathometric profile records were developed in the area extending 40 miles north of the dam at Akosombo, using a Raytheon DE 719 (200 kc) Survey Depth Recorder. These profiles were uncontrolled; visual reference to map features was used for horizontal location.

One objective of the trial survey was to determine the effect of drowned trees and other vegetation on this survey method. It was anticipated that inundated trees and other vegetation may interfere with the sonar system operation, and that decaying vegetation on the lake bottom may act as an insulator, absorbing the sound energy and thus rendering the system inoperative. During the survey, the vessel passed nearby and

directly over large trees and over known forested areas. In all cases, the system yielded high quality, interpretative data, although submerged branches, trees and grass were noted on the chart (Fig. 1). It was concluded that the system used would be totally satisfactory for bottom profiling in Volta Lake. The instrument used (and probably similar instruments), will perform satisfactorily at all depths for precision depth surveys in Volta Lake.

For such surveys it is recommended that a small 10-15 foot shallow draft vessel with outboard motor be available in areas where safe operation of a larger vessel would be jeopardized by inundated trees. A "jet" type engine would be ideally suited for fathometric surveys owing to its shallow draft and non-fouling characteristics. It would require a plentiful fuel supply, however. Because of the lake's magnitude, extensive surveys should include modern electronic positioning instruments to ensure efficiency and positioning accuracy. Tellurometer MRA 1,* MRB 2* (hydrodist) or equivalent instruments are well suited for maintaining positional control during bathymetric surveys, and are also suited for range-line measurements. Transit intersection may be used, but will require more time.

Profiles were obtained between identifiable landmark features for the purpose of checking bottom elevations against

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*These two models are superceded by newer models. Cost of a good used instrument is between US $500 and US $800.

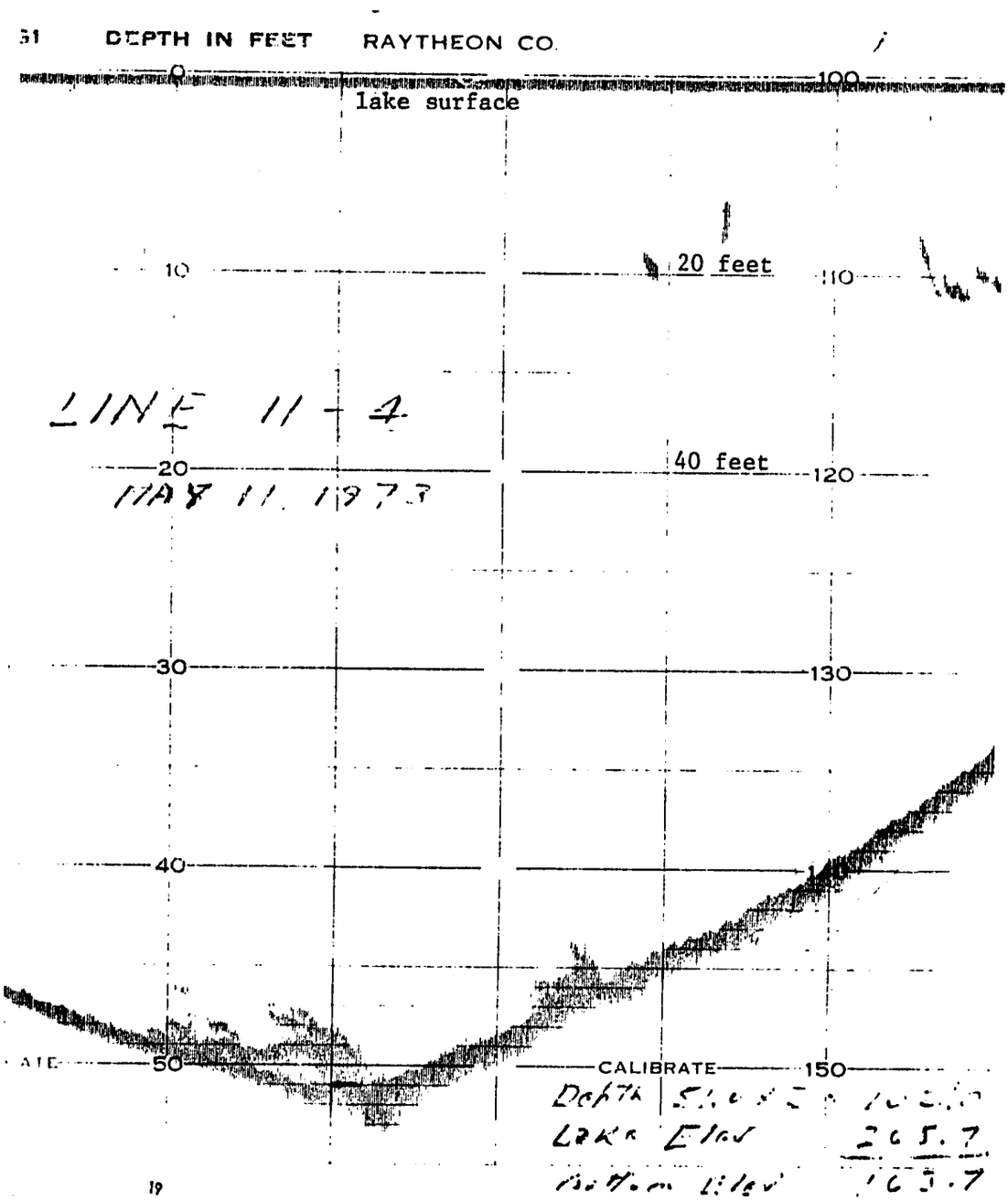

Figure 1. Fathometric profile, Volta Lake.

map contours. In most instances, verified elevations differed from map elevations by 30-50 feet. The significance of this discrepancy is discussed below in the treatment of area-capacity calculations.

It was also anticipated that a means could be developed to monitor the rate of decay of fully inundated vegetation by running profile lines and noting the position, depth and mass of vegetation indicated on the fathometer chart. Review of the charts obtained during the study indicates that this is feasible; however, extreme care must be taken to precisely control the position of the vessel during the survey, and several repetitive lines should be run on each transect to verify the data. These lines could then be repeated at yearly intervals, and the data compared with data developed in the original "baseline" survey to determine decay rate.

Sedimentation Surveys

During the planning and construction phases of the Volta Reservoir, the Geological Survey Department of the Ghanaian government prepared plans to establish and monitor sedimentation ranges throughout the reservoir. However, pressure from other priorities prevented the implementation of this plan. To date, no effort to monitor the deposition of sediments has been made.

On Volta Lake, it seems impractical to predict the sedimentation that will occur, other than on a general basis. Major

contributing streams flow through highly erodable channels. It seems apparent that these sediments will, for the majority, settle in the vicinity of the stream mouths, and will gradually foreshorten the tributary valleys. The effect of this sedimentation will probably be to alter navigation, change shallow water fishing patterns, and reduce the reservoir live storage by a limited amount. The Volta River Project Engineering Report, by Sir William Halcrow & Parners (1955) states that ". . . the capacity of the reservoir is such that no measurable reduction could take place, due to silting, for several hundreds of years." This conclusion was drawn because of the immense capacity and dimensions of the reservoir. Smaller reservoirs in a similar area may suffer significant reduction of storage due to sedimentation.

In the Volta Lake some effort should be expanded in establishing baseline data for flow velocity, sediment transport, and bottom profiles, so that at some later date (five to ten years) comparisons might be made, and the impact of sedimentation projected into future operations of the lake. This information would be useful not only on the Volta Lake, but for planning and design of other reservoir and dam projects in Ghana with comparable watershed conditions.

It is recommended that sedimentation ranges with permanent monumentation be established at the entrance of all major contributing streams (Fig. 2) and at the juncture of the valleys formed by these streams with the body of the reservoir. The

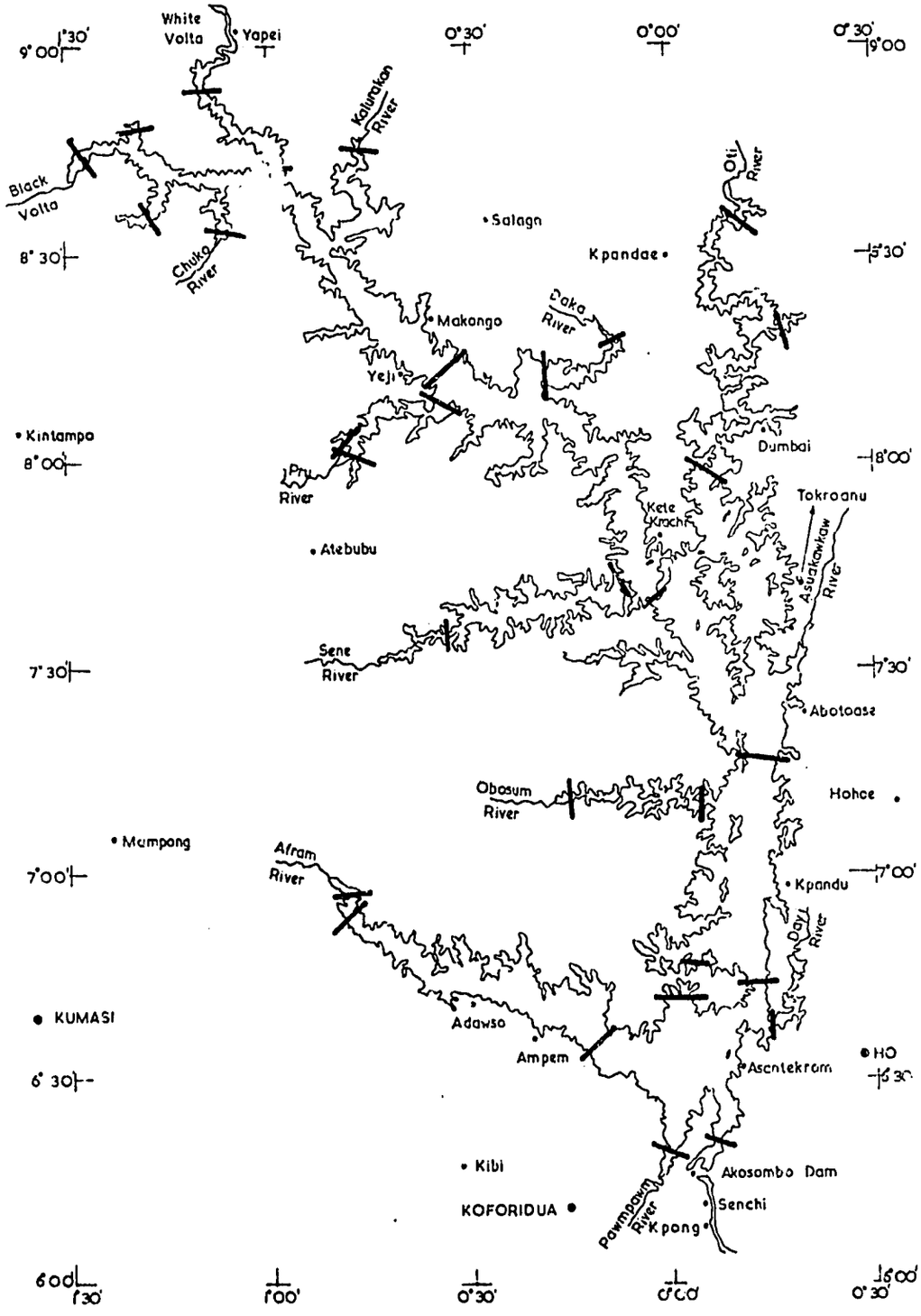

Figure 2.--Tentative location of proposed sediment catchment ponds

stream-mouth profile ranges are designed to monitor the build-up of sediment fans. The ranges located near the main body of the reservoir are designed to monitor sediment migration into the reservoir dead storage area.

Monuments for these ranges should be established 10-15 feet above maximum flood elevation, and the distance between monuments should be measured to 1:10,000 accuracy. Elevations of all monuments should be determined to ± 0.1 foot, relative to an assumed elevation derived from lake level at the time of the survey. All monuments within a given study area should be accurate, relative to each other within 0.2 feet.

The bottom profile of each range should be determined using a continuous chart depth recorder, or sounding lines at 50-foot intervals. Each bottom profile should be surveyed twice, and agreement between all bottom elevation points on the profiles should be within 0.3 foot ± 1/4% depth. Plot bottom profiles at horizontal scale 1 inch = 200 feet, vertical scale 1 inch = 10 feet. At 1/4 point, 1/2 point, and 3/4 point along each range, vertical profiles should be obtained of current velocity and direction, and temperature at points three feet above bottom, three feet below the surface and at 1/4 depth, 1/2 depth and 3/4 depth. A bottom sediment sample should be obtained at each current station (undisturbed, if possible). Savonius or Price-type meters sensitive to 0.1 knot and thermister temperature probe sensitive to 0.2°C can be used.

To visually document bank and stream conditions (stream-mouth ranges only), stereo aerial photography (photogrammetric quality) should be obtained at a scale sufficient for interpretation and graphic measurement.

Two surveys should be conducted: one prior to the start of the rainy season, and one repeat survey immediately after flow returns to average. Continuation of the program would be subject to data review, and in five to ten years a resurvey can be anticipated.

When possible, surveys should be undertaken on calm and windless days. Sediment gages in the form of graduated rods can be driven in recoverable locations. By visual observation on the sediment level of these rods, short-term sedimentation trends may be detected. Some range lines should be deliberately located over tree and brush stands. Although sedimentation data in this area will be minimal, fathometric record of tree profiles could, over time, yield useful data in determining the deterioration rate of inundated trees. Positioning of all range lines, profile "fix" marks, current stations and bottom samples should be correct within five feet horizontally. Prior to, and at frequent intervals during the range profiling, depth recorders should be field calibrated according to manufacturer's recommendations.

Area-Capacity Calculations

Present area-capacity operating information is based upon data presented in the Halcrow Report (Sir William Halcrow and Parners, 1956) and repeated later in the Kaiser Reassessment Report (Henry J. Kaiser Company, 1959). This information was derived from topographic maps based on aerial photogrammetry developed over the project area by the Overseas Survey Directorate in 1951-1953, in cooperation with Ghanaian technical agencies. To evaluate the area-capacity data, it was necessary to first evaluate the method and equipment used to prepare the topographic maps and the specific purpose for which the maps were designed.

Photography at the scale of approximately 1:40,000 was obtained for the mapping by the Royal Air Force and other entities from an altitude of 20,000 feet, using a six-inch focal length camera. From the photography, maps were prepared using a "Multiplex" stereo bridging and plotting system which, from the 1:40,000 photography, should normally be capable of producing 30-foot contours providing field survey elevations are within three feet. The generally accepted statement for accuracy of present-day photogrammetric maps is that 90 percent of all contours shall be correct within 1/2 contour interval. Under these specifications, one would expect an average vertical deviation of less than 15 feet.

Review of source material for the maps in the Overseas Surveys Directorate office in London indicated that the resulting

maps, at 1:50,000 scale with 50-foot contours, were quite sufficient for the requirements of the consulting engineers; namely to provide information for land use studies, a preliminary assessment of capacity, and a preliminary outline of the area to be inundated. They were not, however, sufficient for the calculation of storage volume increments. To this date, no further mapping effort has been completed, and the 1:50,000 map series is the only source of information for which operating data can be developed.

In 1971, UNDP contracted with Institute Geographique National, of France, to obtain new 1:30,000 photography of the reservoir and surrounding areas, and prepare semi-controlled mosaics at 1:50,000 with format coinciding with the existing 1:50,000 maps. Some of the photography was, however, not of acceptable accuracy for photogrammetric topographic mapping. Currently, the Overseas Survey Directorate i obtaining 1:40,000 photography and preparing new 1:50,000 photogrammetric maps with 50-foot contours of the reservoir and surrounding area. However, this mapping is limited to the area north of latitude 7°30', i.e., the northern half of the reservoir, roughly.

Comparison of a representative sample of the 1953 1:50,000 mapping with the 1971 1:50,000 mosaics (which show th e shoreline at the 268-foot elevation) indicates the following:

1. The shoreline, although varying widely in many places from the map, probably encompasses, within reasonable limits, about the same total surface area.

2. In instances on the sample sheets, the 268-foot shoreline, superimposed on the map, ranges from the 200-foot contour to the 350-foot contour.

3. Contour shaping of the land form, compared to the shore outline on the mosaics varies widely.

These discrepancies explain why fathometric profiles obtained during this study were in significant disagreement in many instances with map contours.

The review of the mapping techniques used, and the quality of the finished 1:50,000 maps indicate that the existing area-capacity data now being used may contain significant errors. This is especially the case when the capacity of one 10-foot deep band of storage is considered. The effect of contour error on storage data using the existing area-capacity data can be seen in Table 2. It can be appreciated that if the maps were essentially correct in contour form, but in error by a simple datum change of -10 feet, the following effects would apply:

TABLE 2. Reservoir Areas and Volumes, Volta Lake[a]

Water Elevation, Ft OD	Surface Area Sq. Miles	Surface Area Million Acres	Storage Volume 10^6 Acre Feet	Storage Volume Increments 10^6 Acre Feet
100	95	0.06	1.15	
200	900	0.60	25.5	
250	2230	1.44	74.0	15.5
260	2625	1.68	89.5	17.5
270	3030	1.94	107.0	22.0
276	3275	2.10	120.0	
280	3435	2.20	129.0	
290	3781	2.42	152.0	

[a]Kaiser Reassessment Report (Henry J. Kaiser Company, 1959).

1. The 270-280 foot elevation increment would become the 260-270 increment and would contain a live storage of 17.5 million acre feet, instead of the 22.0 million acre feet as indicated by the record. This is a reduction of 4.5 million acre feet, or about 20 percent. The surface area would be reduced from 3435 square miles to 3030 square miles, a reduction of 405 square miles, possibly resulting in a storage gain due to decreased evaporation.

2. The 260-270 foot elevation increment would contain live storage of 15.5 million acre feet, instead of 17.5 million acre feet, reducing storage by 2.0 million acre feet or about 12 percent. The surface area would be reduced by 395 square miles.

The foregoing is presented only to illustrate the effect that map errors may have on reservoir data. Limited analyses of 1:50,000 map sheets 100, 103, 138, 141 and 121 do not indicate that a uniform datum shift exists, but rather that the contours are sufficiently in error to indicate that the reservoir data may be in error by a significant amount, especially in the lower storage limits.

The significance of error in area-capacity relates to the uses of the reservoir water. At present, the function of the Volta Lake system is primarily the generation of electricity. In the context of this single purpose use, reliable storage data are usually meaningful only when operating in the lower storage area. Additional demands such as flood control, irrigation, recreation, transport and fisheries are being imposed upon the system. It is probable that the zone of critical operation will be widened so that more accurate area-capacity data at all surface elevations will be needed to ensure efficiency in management of the entire use program. It is therefore recommended that a program be undertaken to obtain new topographic data, and to develop new area-capacity operating information within the 248 to 276-foot elevation (live storage zone). The scope and content of the recommended program are detailed below. Two options for obtaining topographic data for the critical zone of operation are set forth.

1) The most economical method of developing contours in the drawdown zone would be to obtain new aerial stereo photography, using a 3 1/2-inch focal length camera, over the entire foreshore of the reservoir if, at any time, it is necessary to draw down to 255-foot elevation. This photography should be panchromatic black and white (or black and white infrared if the exposed foreshore is sufficiently dry), flown at an altitude designed to minimize the number of exposures, yet allow for accurate delineation of the water line. Scale and flight pattern should be designed so that the high water line is visible on all flights.

For contracting purposes, the existing 1:50,000 maps may be used to delineate photo coverage requirements, with a statement to the effect that the 255-foot contour may not coincide with the 255-foot water line, and may not accurately define the required limits of photography. After obtaining photographs, approximate five-foot contours can be interpolated and drawn directly on the photographs, using a desk stereoscope, between the 255-foot water line and the visible high water line. The 250-foot contour can, in a similar manner, be obtained by extrapolation.

Contour trace overlays can then be brought to the scale of the existing UNDP 1:50,000 photomosaics, and matched by shoreline image. From the resulting contour map of the

drawdown zone surface area between contours can be determined by planimeter or digital means, and new area-capacity and evaporation data can be calculated.

2) If the lake will not be drawn down to the 255-foot elevation, a bathymetric survey will be required to define sufficient bottom elevation so that contours down to 248 feet can be drawn. The existing UNDP photomosaic and/or the 1:50,000 maps now being prepared by the Directorate of Overseas Surveys will serve as a suitable base map for plotting contours and determining areas. All horizontal positioning can be referenced to the visible shoreline on the original 1:30,000 UNDP contact prints used in compiling the mosaic. A tentative program for the survey is as follows:

a) Using 15-20 foot shallow draft vessels, develop fathometric profiles from the shoreline out to the 248-foot contour. Profiles should be one-half mile to two-mile intervals, depending on the uniformity of the bottom, starting at a point identified on the aerial photographs. Lines should be normal to the shoreline, or on bearings determined by compass heading. Distance to shore can be determined by range finder (on distances under 600 feet), by sextant, or by electronic distancing instruments (including shore-range radar). Distancing accuracy should be within five percent of the distance to shore.

b) Using photo identification, bearing and distance data, and fathometric charts, the range lines can be laid out on the 1:50,000 photomosaics, and the five-foot contours plotted for 248 to 276-foot interval.

c) From the resulting contour map of the drawdown zone, surface area between contours can be determined by planimetric or digital methods, and new area-capacity and evaporation data can be calculated.

As the location of the shoreline in mapping is influenced by the slope of the terrain, it should not be necessary to attempt recontouring of map sheets whose average shoreline slope exceeds ten percent. Therefore, the existing 1:50,000 maps in the steeper shoreline areas can be utilized in determining area-capacity data.

Navigation and Charting

With the filling of Volta Lake, water transport has become a major means of material and personal transportation in the area. Scheduled ferry and freight service has been established from Akosombo to population centers in the north, and a shipyard has been constructed at Akosombo for service, repair and construction of vessels. Some channel marking and charting has been undertaken to provide navigational assistance to the existing and planned water transport system. The following comments and recommendations are general, based on a limited review of conditions and requirements, and should be developed with the cooperation of the Marine Department, after a detailed review of the transport plan.

In the northern reaches of the lake, the natural ground slope is generally less than one percent, resulting in wide expanses of shallow foreshore. In this area, navigation of deeper

draft vessels is necessarily confined to the inundated channels of tributary streams which, at present, are marked by the remains of trees which bordered the tributary banks. As vegetation decays, the natural demarkation of channels will disappear. It will be necessary to construct a system of navigational markers on those tributaries which are included in transport routes. Furthermore, during periods of high run-off, sediments deposited will be mainly in the upper reaches of the tributary channels, creating a condition which may have significant effect upon the extent to which navigation can be maintained in the tributary areas.

Since no dredging capability presently exists, it seems important that a program be developed for charting and marking these channels and for periodically resurveying the critical areas to determine the rate of sedimentation and the changes that occur in the channel bottom. If such surveys indicate significant sedimentation or changes in the channel's configuration, the shipbuilding program may require review to ensure that design draft of the planned transport fleet is compatible with the anticipated water depth available through the planned transport routes.

In view of the probable obstructions to navigation from sedimentation in the northern reaches of the lake, a bathymetric survey should be conducted in all channels proposed for transport use. This survey should consist of bottom cross-profiles at 100-foot intervals, extending from bank to bank of the stream

channels from elevation 240 OD. Results of the survey should be plotted showing bottom contours at a final scale of 1:50,000 and prepared in a navigation chart series for publication. For accuracy and economy, modern instrumentation and methods should be employed in the survey operation. Recommended instruments and equipment include:

Vessels:
Two, 15 to 20-foot with canopy, equipped with 60+ horsepower motor and fuel reserve. An additional support vessel may be required for surveys of outlying areas, to accommodate survey party living requirements.

Positioning Instruments:
Cubic Autotape, Motorola RPS system, Del Norte Trisponder System, Tellurometer Hydrodist, Towill Hydrographic Position Plotter or equivalent system.

Bottom Sounding:
Raytheon DE 719 Fathometer, Kelvin Hughes survey depth recorder, Ross survey depth recorder, or equivalent.

Support Equipment:
Surveying instruments and supplies, portable radios, twelve, 12-volt automobile batteries, gasoline generator and battery charger.

Personnel Requirements (excluding support and facility staff):
Two survey engineers
Two vessel operator-technicians
Two survey technicians

During the initial survey, control positions and water level staffs should be permanently established, with elevations and coordinates based on the regional horizontal and vertical datum. Additionally, survey markers should be established on existing

trees and landmark features to facilitate later surveys and navigation by sextant methods. These markers should be large enough to be clearly visible to the naked eye, and should be numbered for positive identification. Coordinates of the markers should be determined during the initial survey, and their position and identification markings should be indicated on the navigational charts.

If inundated trees presently used as channel markers disappear, permanent towers should be established and coordinated to serve as navigational and survey markers. After completion of the initial survey and charting, the process should be repeated on a limited basis after the next run-off season to determine the pattern of sedimentation and channel changes that may be expected. The channel charts should be revised. During chart revision, critical areas can be identified; subsequent surveys can be limited to these areas or possibly eliminated for several years. Complete resurveys of the upper reaches of the tributaries will probably be required at three to five-year intervals, depending on the effect of sedimentation; however, valuable information for chart updating can be obtained by recording fathometric data during routine ferry runs, using the navigational markers for periodic sextant location of the vessel's position.

During the channel survey operation, it is also recommended that bathymetric maps be prepared in the vicinity of

existing and potential population centers for planning approach routes and docking facilities. The existing 1:50,000 series maps, which show 50-foot contours prior to inundation are not sufficiently accurate for this purpose, and are suitable only for general determination of bottom configuration.

Seismic Considerations

Practically all geological and geophysical data available in the Volta Lake region appear to have been developed from on-site geological surveys and analyses of test borings. With regard to the concern for seismic stability and dam safety, it appears that some recent developments in the technologies of geological survey and seismic measurements should be considered.

Side-looking radar imagery is being used effectively in the identification and analysis of fault patterns occurring over large areas. The system is airborne, but is essentially unaffected by cloud cover. The apparent ability to penetrate forest cover, coupled with extremely wide coverage imagery, results in a detailed overview of the subject area. This is practically impossible to obtain by conventional photographic means, especially in tropical locations. Side-looking radar imagery, coupled with photogeologic analysis of available aerial photography, would be an invaluable adjunct to existing information regarding mineral resource development and seismic conditions.

Prior to inundation, geologic exploration of the lake site required tedious field investigation on a point-to-point basis. Geologic patterns were then developed by projection and interpolation between points, with intensive field exploration in specific areas of interest. This survey method is a long-term and costly process, and in such a large area, the cost and time limitations for detailed investigation becomes prohibitive.

Seismic sub-bottom profiling of the geologic formations underlying Volta Lake is suggested as a means to quickly and economically develop detailed geologic and geophysical data for groundwater, mineral and seismic studies to supplement existing data and proposed study programs.

Bottom conditions of the lake appear amenable to sub-bottom penetration, and it seems reasonable to expect that detailed geological information could be developed to a depth of at least 300 to 400 feet below lake bottom. Sub-bottom profiling equipment could be operated on 30 to 40-foot vessels now available on the lake, and, owing to the apparent favorable conditions, it appears that 20 to 30 miles of high resolution data could be developed per day.

To obtain maximum value of a sub-bottom program accurate horizontal positioning is necessary. It is recommended that such a program should be done concurrently with sedimentation range and bathymetric surveys, so that the survey navigation

systems and surveyors would be available for positioning during sub-bottom profiling.

Bottom penetration and resolution are dependent on the frequency of the sonic energy, and penetration is also dependent on adequate power of the sonic energy source.

For sub-bottom profiling on Volta Lake, equipment should be available to operate in various frequency ranges, either singly, simultaneously or in multiplex mode so that the quality of data can be optimized throughout the varying bottom conditions that may be encountered. The following specifications are tentatively recommended for sub-bottom profiling.

1) For penetration of 0-25 feet:
   frequency - 5 KC
   pulse - 0.1 to 0.2 millisecond
   power - 10 KW peak
   resolution - 1 to 2 feet

2) For penetration of 0-100 feet:
   frequency - 1 to 2 KC
   pulse - 0.2 to 0.3 milliseconds
   resolution - 2 to 3 feet

4) For penetration of 300-500 feet:
   frequency - 0.5 to 1.0 KC
   resolution - 8 to 10 feet

Analysis and interpretation of data gathered by the foregoing or similar systems could result in a detailed understanding of layering of underlying strata and sediments, faulting and fault location. In the vicinity of existing borings, rock type can be tentatively identified, and reasonable

interpretation of rock type may be extrapolated throughout the lake bottom by comparing the sub-bottom chart data with data developed from boring logs. If no boring logs are available, a qualified marine geologist can interpret sub-bottom chart data to define the limits and interfaces of characteristic features, and by reference to experience, can identify probable rock type. If a boring program is planned for future geologic studies, review of the sub-bottom data will provide extremely useful information for locating and spacing borings for maximum utility and economy. Upon completion of a boring program, provided all borings are accurately located, the sub-bottom data can then be re-analyzed, using the boring logs for more positive interpretation of rock types.

With respect to the hazard of earthquakes and tectonic movements, the dam at Akosombo is presently monumented so that downstream deflection or slip can be detected and measured by conventional surveying methods. In recent years, sophisticated laser alignment and electronic tilt measuring devices have been developed to monitor movement of major structures, relative to adjacent structure components and to distant monuments in the valley walls. With respect to the concern for seismic stability, it may be advisable to review the existing program to determine its adequacy, and to install additional devices which are now available.

In addition to seismographic stations already installed, it may be desirable to install sensitive tilting devices in the lower levels of the power structure and spillways. These would furnish records of permanent strain caused by earthquake effects. These instruments are accurate, simple to install and read, and are relatively inexpensive. The BAC Electrolevel, manufactured by British Aircraft Corporation, is a proven device. It is recommended that several of these instruments be installed as part of any seismic monitoring program that may be implemented. They should not be located in areas that are affected by local temperature changes, especially those locations exposed to direct sunlight, as local expansion and contraction yield tilting information which is not representative of foundation conditions.

4. Changes in Mineral Cycling Associated with the Formation of the Volta Lake

Introduction

The activities of modern man frequently produce side effects less beneficial to human welfare than the purposes for which the industrialization is undertaken. Among the unwelcome side effects have been many that involve changes in mineral cycling: eutrophication following pollution by phosphates, nitrates and other nutrients; dangerous concentrations of toxic heavy metals in aquatic systems; and salinization of irrigated lands caused by poor drainage and flushing of various soluble salts. These impacts involve changes in the mineral cycle, and the examples given involve the enrichment of chemical substances above their naturally occurring levels. On the other hand, agricultural activities can, if carried out over a sufficiently long period of time, disrupt normal mineral cycling by decreasing the availability of nutrient salts in the soil. In Ireland, large areas of infertile bog cover land that grew good crops until a combination of human and natural events reduced the availability of mineral nutrients and permitted the establishment of acid-loving peat mosses. There are good reasons for believing (Clark, 1952) that a purely human influence on

mineral cycling was responsible for the decline of the classical civilizations of Greece and Rome.

The construction of a large tropical reservoir must also have major effects on the mineral cycle. It is the purpose of this report to examine effects, to determine the likelihood of their occurrence, and to assess their seriousness.

The application of mineral cycling concepts is relatively new. The following two sections are devoted to a brief exposition of mineral cycles and to the relation of these and African inland waters.

Mineral cycling.--The effects of the creation of the Volta Lake may be viewed against a more general background of what mineral cycling is, and the different sorts of mineral cycles that have been identified on our planet. The substance of which the earth, the waters, the air, and we ourselves are composed is not static, but is in a constant state of flux or dynamic exchange between the different pools or reservoirs of each chemical element in the entire system. Nitrogen, for example, constitutes about 78 percent of the atmosphere. In the gaseous form it cannot be used for plant growth, and the combined forms of nitrogen out of which plants make the proteins which animals eat are synthesized by a very limited number of blue-green algae and bacteria. Some oxides of nitrogen and possibly also some ammonia are produced by

lightning flashes, meteorites and hot lava surfaces, or emanate from volcanoes, but the quantity fixed by these inorganic mechansims seems to be a small part of the total.

Most of the combined nitrogen in the bodies of plants and animals is returned to their environment by excretion and decay, but a small part is incorporated into sedimentary rocks. On the average, sediments contain appreciably more nitrogen than igneous rocks, so that the transformation of igneous material to sediment involves some net diminution of the nitrogen store of the atmosphere. Some of the sedimentary nitrogen recycles through uplift and erosion of sedimentary rocks. The fate of the balance is uncertain, although some of it probably enters molten rocks deep in the earth.

The cycle of carbon is similar and even better known. Although the atmospheric store is very much smaller, it plays a role similar to that of atmospheric nitrogen. Even quite small-scale and short-term cycling of carbon may be of considerable significance, such as the accumulation of carbon dioxide in the deep water of a seasonally stratified lake, or the daily pulse in the rate at which carbon dioxide is used by green plants in photosynthesis.

Not all elements move through the atmosphere in such large and important quantities. Except in regions of industrial pollution, phosphorus, for example, enters the living part of the world in aqueous solution after having been removed

from rocks by weathering. It is lost to the living part of the world by precipitation in marine sediments, the total return from the sea to the land by the activities of fishermen and fish-eating birds being apparently considerably smaller than the delivery from land to sea by rivers (Hutchinson, 1950).

The mineral cycles briefly described above are in fact very complex. The host of reactions between groundwater and rocks, the infinite variety of biochemical pathways, are only incompletely understood. All organisms, including ourselves, are agents of mineral cycling, and are affected in distribution, well-being and abundance by it. The circulation of the atmosphere, of the oceans, of lakes, the flow of rivers, are all mechanisms of mineral cycling, as are the great earth movements of mountain building and continental drift.

Geochemistry of African waters.--The past fifteen years have greatly improved our understanding of the reactions controlling the composition of inland waters. The general picture is given in recent books by Garrels and Mackenzie (1971) and Stumm and Morgan (1970), and the new understanding has been applied to tropical African waters in a still unpublished thesis by Kilham (1972).

Over a large part of tropical Africa the rocks are either readily soluble volcanics of Miocene or younger age, or else deeply weathered ancient rocks, many of them pre-Cambrian crystalline and covered with a thick mantle of more or less

kaolinitic soil. All of these rocks may be thought, as a first approximation, to consist of a cation-aluminosilicate compound, which reacts with the dilute carbonic acid of rainwater and groundwater to yield a solution of cations, bicarbonate ions, silicic acid, and a solid residue of aluminosilicate:

$$\text{cation Al Silicate} + H_2CO_3H_2O \longrightarrow$$
$$HCO_3 + H_4SiO_4 + \text{cation} + \text{Al Silicate.}$$

Over wide areas nepheline ($Na_3KAl_4Si_4O_{16}$) or rocks similar to it are very common, so the resulting solution is essentially one of sodium bicarbonate, with much smaller amounts of potassium bicarbonate. If such a water is concentrated by evaporation, it may become very alkaline indeed, but the relative proportions of the different ions in it will not change much in the process. In a few places, such as the volcanic areas around Lakes Kivu and Edward, there are rocks rich in high-magnesium and potassium minerals, such as magnesium olivine (Mg_2SiO_4) and leucite ($KAl[SiO_3]_2$) and magnesium and potassium ions are more abundant in the resulting solution.

The old rocks are chemically more diverse, and no single cation tends to dominate them, so waters are formed by weathering in which sodium, potassium, magnesium and calcium are present in more or less equal abundance. The thickly weathered mantles of these rocks are rich in clay minerals such as kaolinite, which breaks down in the presence of dilute carbonic acid

to give gibbsite and silicic acid but no cations:

$$\underset{\text{kaolinite}}{Al_2Si_2O_5(OH)_4} + 5H_2O \longrightarrow 2H_4SiO_4 + \underset{\text{gibbsite}}{Al_2O_3.3H_2O}$$

In such a locality, silica becomes a major component of the dissolved material of waters.

Local variations of these two general themes are to be found in areas of sedimentary rocks, such as part of eastern Zaire, and probably much of Ghana as well, where leaching of salts from the old sediments gives waters a distinctive character, or where the climate is so dry that weathering of rocks is much inhibited. This is the case in the arid part of north-central Tanzania around Basotu, where the waters are rich in sodium chloride from evaporated rainwater. In basins of extreme evaporative concentration such as Lake Magadi in Kenya or Lake Mahega in Uganda, differential precipitation of ions in the form of the less soluble salts may change the ionic ratios somewhat, though sodium, chloride, and bicarbonate are little affected in their proportions to each other.

In Ghana, the rocks are almost all of great antiquity. Most of them are covered with a deeply weathered kaolinitic mantle. In no part of the country is the climate dry enough for pronounced evaporative concentration, although some concentration has occurred at Lake Bosumtwi, probably of an original water influenced in composition by the local occurrence of pumiceous rocks.

The Volta Lake

This treatment considers the effects of the Volta Dam on mineral cycling, first with respect to the cycling that occurs within the lake itself, and then with respect to its influence on the mineral economy of the outside world.

Internal cycling within the lake.--When the dam was closed, the area to be flooded was not bare earth, but was covered with a considerable mass of vegetation, most of it alive. When submerged, this vegetation died, and its substance began to decompose, soft parts like leaves very rapidly, woody parts more slowly. The decomposition of this mass of organic material demanded a quantity of oxygen greatly in excess of that dissolved in the water of the lake, and a very severe oxygen depletion developed within four weeks. The deoxygenation had been foreseen (Volta Basin Research Project, 1964), but not the speed with which it developed (Ewer, 1966). A similar rapid depletion of oxygen has occurred in some other tropical dams, but not all.

The depletion of oxygen disappeared as the readily decomposed organic matter was consumed, and the necessary oxygen provided by diffusion from the atmosphere and photosynthetic activities of aquatic plants. One might wonder, perhaps, why photosynthesis does not compensate completely for decomposition. It may for a while; in the early stages of filling, the oxygen content of the lake water actually rose,

to 300 percent saturation. Depletion comes about because the mass of plants in a terrestrial system is usually very much greater than that in an aquatic system of similar organic productivity. One does not get a simple replacement of plants that cannot tolerate submersion by plants that can, because there will be a much smaller mass of plant material after flooding, and it is the decomposition of the balance that creates such a large, unsatisifed biological oxygen demand.

Decomposition of the terrestrial vegetation has the effect of releasing to the water the nutrient substances, such as phosphorus, nitrogen and potassium, of which the plants were composed. Just as one can get a few good crops by burning a forest and cultivating in the ashes, so the production of the lake during its early years, after sufficient oxygen returned to the surface layers of water to encourage plant growth, was very high. In terrestrial tropical ecosystems, most of the nutrients are incorporated in the bodies of living organisms, unlike temperate or arctic systems, which usually have a much larger part of their nutrient pool in the soil. Even in temperate reservoirs there is usually a transitory phase of high productivity during the first few years after the dam is closed.

The initial rich dose of nutrients does not remain in the watermass, to be continually recycled between actively growing plants and the water in which they are suspended. Much of it gets washed out of the reservoir and on downstream. Much enters into an equilibrium with the submerged soil, the sediments

that immediately begin to accumulate on the floor of the new lake. It was once thought, from preliminary studies in the East Indies, that submerged tropical soils were like terrestrial ones, poor in nutrients. Studies of East African lake sediments show that this does not have to be the case. The planktonic detritus of tropical lakes is not commonly decomposed to an unusual extent, and the preservation of planktonic organisms can actually be very good, as it is in Victoria (Bradley, 1966).

Dynamic exchange between the water and sediment is very important in controlling the productivity of an aquatic system. Few studies would lead to so much understanding of the internal economy of the Volta Lake as a serious investigation of the rate at which nutrients are being lost to the sediment, and the extent, time and location of regeneration of nutrients to the water. It is in the solid phase (e.g., sediments) of an aquatic ecosystem that most of the phosphorus is to be found (Hayes _et al._, 1952), and any realistic appraisal of the possible eutrophying effects of deliberate fertilization of the water, or inadvertent fertilization with sewage, would require a serious investigation of the mud-water reactions. Such an investigation is of scientific interest, but until such time as eutrophication seems imminent, it does not appear justifiable. A dynamic study of the internal nutrient economy might disclose that phosphorus was in short

supply in the water and abundant in the sediment. This finding seems probable. However, it is most unlikely that anything could be done to reverse that state of affairs.

Deliberate fertilization of lakes with phosphorus can be carried out on a small scale, although it is not economical. On a lake of this size with a very high rate of through-flow, it would be hopelessly expensive. Indirect chemical or physical manipulation of the system to increase the rate of release of phosphorus from the mud and its transfer to the illuminated upper water where it can be used for plant growth, is no more likely to be a feasible undertaking.

Inadvertent eutrophication is not likely to occur under present conditions, but the establishment of large cities or intensive industrial agriculture in the catchment area of the lake could change the cycle of mineral nutrients. It is just such nutrient-poor, soft-water lakes as this that are most easily influenced by a continual addition of massive quantities of nutrient salts.

The history of the Volta fisheries, with an initial period of yields increasing to a high level, and subsequent decline, is probably a direct consequence of the early changes in mineral cycling resulting in transitory enrichment. It is unlikely that any amount of careful regulation of the fishery would sustain the yields of the peak years, because the lake, after its water comes to a chemical equilibrium with the

sediment, simply will not support the same high levels of photosynthesis that nourished the fish during the peak production.

There is some suggestion from the unpublished chemical data of the past three years that a permanent stratification may be developing at the Ajena station. The seasonal oxygen depletion has become progressively more severe, and there is a slight but significant increase in the concentration of sodium and potassium in the deepest water. This permanent stratification, if it does occur, will form a small puddle of nutrient-rich, oxygen-poor water in which mobilization of sedimentary iron and manganese will occur. As the years go by, the concentrations of these metals might become very much higher than the few parts per million which were dissolved in the water leaving the spillways for a few months in 1969.

This should cause no major problems or advantages, because the area of deoxygenated water at these depths is likely to be small. It is worth watching for, however, and provides, by itself, sufficient justification for continuing the hydrographic observations that formed an important part of the hydrobiological observations of Dr. Biswas.

Apparently no investigations have been made of internal waves in the lake. Such waves are a common feature of stratified lakes, and because the density difference between two layers of water is always very much less than the density difference between water and air, they have a much greater amplitude than the

wind-waves and seiches of the water surface. Internal waves are the main mechanism for generating the vertical turbulence which transfers mineral nutrients from the deep water to the zone of photosynthesis. This may also have considerable practical importance in determining whether or not hypolimnetic water will reach the level of a spillway, and in controlling the occurrence and location of fish kills such as have affected the lower part of Lake Volta in some years. Neither of these practical consequences is likely to be as important now as in the initial years when the lake was generally deficient in oxygen, but they might become locally important again if permanent stratification does develop at Ajena.

For public health reasons, there has been considerable spraying of persistent insecticide in the Volta Basin. Compounds like DDT are not readily decomposed in water, and they are concentrated up the food chain in at least some aquatic systems. There is some interest in this matter in the Volta Lake Research Project. Common prudence requires that the interest be developed into an active program of monitoring insecticide levels in at least the fish and fish-eating birds of the lake. Obtaining, maintaining, and operating a laboratory for insecticide measurement is not to be undertaken lightly and it would probably be more satisfactory to send samples away for analysis. It might be possible to establish a joint program with Dr. Deelstra of the Chemistry Department, l'Université de Bujumbra, who has similar interests and similar

problems with respect to pesticide accumulation in Lake Tanganyika.

Changes in mineral cycles below the dam.--The transitory changes in nutrient cycling discussed above must have profoundly affected the composition of the river water below the dam. It is likely that even the conditions in the river after the lake comes to a chemical equilibrium will differ from those before the construction of the dam for at least two reasons. First, the area of the Upper Volta drainage exposed to erosion has been reduced by the area of the lake. Second, sedimentation on the lake certainly removes a large, although unmeasured, .rt of the nutrients that enter it.

It is regrettable that the present careful program of chemical monitoring was not instituted before the dam was closed. Excellent data have beer collected by the Water and Sewage Department at the Kpong intake, but there is no adequate pre-dam information with which to compare them. Even a few years of pre-dam analyses would permit one to place bounds on the cycling effects of the Volta dam that are now impossible. Pre- and post-dam impoundment data for several major tributaries are also needed in order to assess the effects on mineral load and water chemistry caused by land use and climatic changes after impoundment.

One of the few recognizable problems of mineral cycling in the Volta experience occurred late in the period of oxygen deficiency. Iron and manganese were rendered soluble by the

reducing conditions, and appreciable quantities of these metals were present at the waterworks intake, Kpong, when the spillways were open. In 1969, for example, the iron content rose to 0.70 parts per million on January 6, and the manganese content to 1.3 parts per million on August 11. With oxygenation of the lake, this problem disappeared and is not likely to recur unless permanent stratification develops at Ajena on a very large scale.

Other cycling problems, both realized and potential, result from stabilization of flow in the river. Normally, the discharge of the Lower Volta to the sea varied with season by a factor of more than one hundred. At high stage, extensive areas of bottom land and lagoon were flooded with silt-laden water; the junction between fresh and salt water stood far to seaward in the estuary, and a considerable volume of light, fresh water spread over the adjacent surface of the ocean.

While the dam was filling, the river flow was stabilized at a very low level, and the underlying wedge of salt water advanced far up the estuary. Since filling, flow has been stabilized at a high level, but there has been no flooding of the adjacent lowlands, nor will there be as long as the dam lasts.

The regulated flow is likely to have reduced the supply of nutrients to both the low-lying farmland and the lagoons. The extent of such reduction cannot be determined for lack of pre-dam chemical data. The Volta is not likely to carry such

proverbially rich silt as the Nile, and it is possible that the fertilizing effect of the seasonal flooding was slight. Because of inadequate pre-dam data there is, however, no really effective way in which the Volta River Authority could defend itself against a charge of serious harm to the downstream farmers and fishermen.

Changes in the salinity boundary have a profound effect on the distribution and abundance of the clam Egeria, which grows best in fresh water, but which breeds successfully only under slightly brackish conditions. Under the present flow rate, there is an adequate but localized breeding area, from which the young clams can be carried to upstream feeding grounds by fishermen. There is some possibility that the flow will be great enough when all turbines are operating to keep the salinity interface outside the estuary, which would prevent the clam population from maintaining itself without human assistance.

It has been claimed that Lake Nasser injured the marine fisheries of the Mediterranean by reducing the flow of nutrients. Such a direct effect is less likely in Ghana, because nutrients are provided by upwelling water. The riverine contribution should be less important. Pople and Mensah (1971) have shown that upwelling depends on evaporative concentration of surface water over a column of uniform density. Under pre-dam rainy season conditions, fresh Volta water would ride over the salt water beneath and prevent upwelling. Under present conditions of stable flow, the amount of upwelling and its distribution

in time and space must be very different. It would be highly desirable to investigate the effect of the dam on the hydrography, nutrient supply, and fish production of the adjacent sea. Once again, the difficulty of the task is greatly increased by the lack of adequate pre-dam data. This type of effect is one that should certainly be considered by the designers of any tropical dam. The tropical oceans are chronically short of nutrients except where upwelling occurs, and anything that reduces, increases, or changes the distribution of upwelling is likely to be important.

Potential salination problem in the irrigation of the Accra Plains.--The proposed irrigation of the Accra Plains may produce the first serious and clearly chemical problem. At present, the flow of water on the Plains is from the atmosphere, through the soil to the rivers and the sea. The small amount of dissolved material that comes down in the rain, together with the much larger amount weathered from the rocks and soil, is carried away to the ocean.

Under conditions of irrigation, this flow will be reversed. River water with a small but not negligible content of dissolved salts will flow over the land, from which the water will evaporate and be transpired by plants, leaving the dissolved material behind. If no provision is made for the removal of this dissolved material, by flushing the soil with irrigation water in excess of plant needs to wash away salts, there will be a gradual accumulation of salts in the soil. With respect

to the dissolved plant nutrients, this will be a piece of good fortune. But the ability of most plants, including many important crop plants, to tolerate common salt (NaCl) is strictly limited. A soil can become so charged with this substance through careless irrigation that it will no longer sustain agriculture.

In Ghana, the care needed to avoid such salt accumulation is less than it would be in the desert of the southwestern United States or arid interior Asia. But the rainfall of the Accra Plains is low (if it were not, irrigation would not be considered), and it is very important that future irrigation be designed with a clear understanding of two necessary steps: getting the water to the land, and getting the salt out.

Conclusion

The Volta Dam does not seem to have caused serious problems of mineral cycling. The nutrient-poor status of the lake water inhibits fish production in the lake, but this is more a fact of life than a man-made problem that could have been avoided.

Accumulation of DDT in at least the upper levels of the Lake Volta food chain should be monitored immediately.

Mineral cycling has been most affected below the lake. The effect of the dam on the position of the interface between fresh and salt water in the estuary is well understood, but other effects on the river, the estuary and the ocean are less clear. A small part of the water chemistry research effort

that has been expanded on the lake since it began to fill, if applied in the previous five years, would have answered many questions about mineral cycling that are now unanswerable.

Continued attention to the hydrobiology of the lake with particular emphasis on nutrient cycling seems to be justified. If deliberate or inadvertent eutrophication should ever become possible, a much better understanding of nutrient cycling will be vital.

5. Plankton in the Volta Lake*

Introduction

The objective of the review of knowledge on plankton in the Volta Lake was to evaluate the need to stimulate plankton growth or to regulate its abundance. To accomplish this objective several aspects of Volta Lake limnology were reviewed: physical characteristics of the lake, the lake's climate, the lake's nutrient status, and mineral cycle. Existing data on plankton occurrence and fluctuations, use of plankton by fish, and the role of plankton in water usage were reviewed and analyzed.

Several organizations and many people have worked on the lake. As a consequence, reports and especially data are not available at one place. Fortunately, Dr. Gernot Bretschko, UNESCO Consultant, has reviewed more than 200 publications and reports and he is preparing a comprehensive report on the limnology of Volta Lake.** In the preparation of the present review, 29 publications, three manuscripts, and 24 reports were

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**Dr. Gernot Bretschko (IBP-Labor, Innstr. 63B, 6020 Innsbruck, Austria) will present this work in a document to be entitled "The limnology of a large tropical man-made lake; Lake Volta, Ghana."

reviewed, and 19 people concerned with work on the Volta Lake were interviewed. In view of the pending report by Bretschko and the excellent annotated bibliography by Aziz (Appendix III), a more detailed review of the data was not necessary.

This report presents interpretations and evaluations of existing data, conclusions, and suggestions for additional research work which would increase understanding of the dynamics of the lake, as well as help predict conditions in other tropical reservoirs.

Pertinent Physical and Chemical Observations

Volta Lake started to form with the closing of the dam in 1964. It has a complex dendritic morphology due to a number of tributary valleys which flooded. The surface area is about 8,700 km^2. Viner (1970) gives an average depth of 30 m and Entz (1969) a mean depth of 18.9 m. In view of the extensive shallows the latter figure is probably the more accurate estimate. The total volume is about 165 m^3 and 40 percent is at depths of 0 to 9 m. Thus the euphotic zone, which extends to 6 m, comprises a sizeable percentage of the volume. The annual drawdown exposes some 500 to 1,000 km^2 (6 to 12 percent of the total area) of the littoral and this is important to the lake's productivity (Lawson, 1970)

Entz (1969) divides the lake into three main sections: (1) the lacustrine below Kpandu; (2) the middle section between Kpandu and Kete Krachi, which is lacustrine except during the

rainy season when it is semi-riverine; and (3) the upper part above Kete Krachi where semi-riverine conditions predominate. The other lake arms would probably fall into categories (2) and (3).

The strong northerly Harmattan winds, usually of December-January, and heavy rains of June-September are important external factors affecting the lake (Entz, 1969). The Harmattan winds can cause mixing to the bottom and increase the dissolved-oxygen content of the deep waters. The heavy rains lower water temperatures and thus facilitate overturn; large quantities of solids, colloidal and dissolved materials are washed from the land, greatly increasing turbidity, and supplying nutrients. Turbid waters move southward from the northern lake during the flood period. Maximum turbidity is found in the old river channel.

During the first years of the lake nutrient levels were quite high, dissolved-oxygen content was very low at depth, and hydrogen sulfide was present at depth due to the decay of the flooded terrestrial vegetation. Conditions now appear to be stabilizing. There has been an increase in transparency, as measured by Secchi disc; a decrease in color, largely associated with decrease in iron; and a great decrease in hydrogen sulfide. Dissolved oxygen is also present now at depths where anaerobic conditions formerly existed.

Total alkalinity gradually increased to a stable level of around 45 mg/l $CaCO_3$ by early 1966, ammonia became progressively more abundant in the surface waters up to 1966 and then decreased, and surface orthophosphate concentrations decreased by almost half after mid-1966 (see Figs, 3 and 4, Lawson et al., 1969). The abrupt decrease in phosphate to a new low in 1966, which has persisted, seems odd but no information is available to explain the phenomenon. According to Czernin-Chudenitz (1971) the open waters are now relatively poor in phosphate and nitrates. Biswas' (MS) final report shows that phosphates averaged from 0.14 to 0.23 mg/l, 1964-1966, and decreased to 0.02 to 0.05 by 1970-1972 at Ajena. There is no clear trend in nitrate data; however, concentrations fluctuated between 0.03 and 0.07 mg/l 1964-1971, and were 0.10 in 1972. Most nitrate concentrations were between 0.01 and 0.08 mg/l in the upper 10 m in January-March 1973. Phosphate was not present in the upper 20 m at Ajena, January-March 1973 (VLRP, 1973). Entz's (1969) conclusion that chemically Volta Lake is oligotrophic seems valid. It should also be observed that the low dissolved-oxygen concentrations reported from the bottom waters should not have the same trophic significance attached to them as for temperate lakes. Decrease in hypolimnetic oxygen in temperate lakes may be associated with increasing eutrophy as plankton decays in the depths. Low dissolved-oxygen in Volta Lake has been caused by decay of terrestrial vegetation.

Phytoplankton

From comments in annual and quarterly reports of the Volta Lake Research Project, it is evident that the phytoplankton was sampled by a number of people. Unfortunately, few data are presented in the reports. Because of the large size of the lake, as well as problems of available transport and boats, which were not in operation for considerable periods, many areas were not sampled. Other areas were sampled infrequently. The most consistent sampling has been at Ajena in the southern basin near Akosombo. On the basis of sampling from Ajena into the northern area at Yeji, Biswas (VLRP, 1972) concluded that Ajena was reasonably comparable to other areas. Undoubtedly he was referring to the open lake. Another problem is that it is not possible to make a direct comparison of some of the results. For example, Rajagopal (1969) used a No. 5 silk bolting cloth net, whereas Biswas (1970) collected with a water sampler and observed plankton with an inverted microscope.

There appears to be general agreement that considerable changes have occurred in the phytoplankton. More than twice the number of taxa have been found in the lake as compared with the river prior to impoundment (Biswas, 1970).

Diversity increased from 34 to 84 taxa. Especially important have been increases in number of species of green and euglenoid algae. The number of diatom species decreased, although

many of those identified for the river may have been periphytic species.

Apparently the blue-green, Anabaena, was dominant in the river prior to impoundment. Since impoundment some green algae, Actinastrum gracilimum, Ankistrodesmus falcatus, Scenedesmus bijugus, were dominant in 1965 to 1966 (Biswas, 1970). Flagellates were also important in this early period: Cryptomonas erosa was dominant in September, 1965, and Peridinium africanum dominant in March and July, 1966. Diatoms, mainly Synedra acus, assumed dominance in 1967, although the blue-green, Microcystis, was a major species at Sene and near the dam. Oscillatoria was reported as abundant at Akuse, Sene, and Oti in 1968. By 1969 the blue-green, Lyngbya limnetica, had appeared as a major species. This blue-green has been dominant in most collections, 1970 to March 1973. Occasionally Cryptomonas erosa or Synedra acus were most abundant, but only briefly. Blooms of Microcystis were reported at Kete Krachi and in the Afram arm in 1971. Lawson et al. (1969) showed an increasing blue-green algae gradient into the Afram arm in 1966. Viner (1969a) concluded that diatoms were important in the deep water areas of the southern basin, whereas blue-greens were dominant in the shallow waters of the north. His conclusion, however, was based on only two transects of the lake in 1966. The Institute of Aquatic Biology data suggest that the deep waters of the southern basin are not as rich in algae as the northern waters.

Biswas (1970) concluded from his data that the lower reaches were quantitatively richer in plankton than the upper ones.

Data presented by Lawson et al. (1969, Fig. 2) indicate a very unstable condition with numerous phytoplankton-maxima in 1964-65. Conditions seemed to stabilize, at least at Ajena, starting in 1966 with peak phytoplankton abundance occurring annually in October-November.

The instability in the phytoplankton in 1964-65 undoubtedly reflected the progressive decay of the flooded terrestrial vegetation with release of nutrients into the euphotic zone. High color associated with iron, which limited light, probably limited full utilization of the nutrients. The fact that peak phytoplankton abundance now occurs in October-November, after the rains and not after mixing caused by the Harmattan winds, suggests that phytoplankton abundance is closely tied to the nutrient inputs during the flood period and not to the mixing of nutrients from the bottom waters into the euphotic zone. Thus the productivity appears to depend to a great degree on external conditions.

Many of the species which have been reported have been associated with nutrient-rich waters or at least with rapid recycling of nutrients. The phytoplankton counts at Ajena have been relatively low, around 200-500/ml with peaks around 1,000/ml, and they are similar to those of oligotrophic-mesotrophic lakes. The data for the Ajena station show that phytoplankton increased to a maximum in 1968 and then decreased to a low level in 1972

(Biswas, MS). Nevertheless, we do not know about the productivity, i.e., the turnover time of the population, nor the extent of cropping by zooplankton and fish. The data tend to support the idea that the arms and shallow waters are more productive than the deep open waters. Bretschko (1972) reported that the sponge Corvospongilla bohmii had become abundant and that this indicated high phytoplankton production in the shallow areas of the lake.

The importance of phytoplankton is not known although it comprised nine percent of the food of fish (Lawson et al., 1969). It must provide food for many invertebrates and contribute to the periphyton, when it becomes attached.

Zooplankton

The zooplankton of Volta Lake is not well known. Some data are available for the early years of impoundment (Proszynska, 1969; Lawson et al., 1969) and mention is made of studies in very general terms in the annual reports of the Institute of Aquatic Biology and quarterly reports of the Volta Lake Research Project. Organisms usually have been identified only to genus. These include the Copepoda, Cyclops and Diaptomus; the Cladocera, Bosmia longirostris, Bosminopsis dietersi, Moina, Diaphanosoma, and Ceriodaphnia; the Rotifera, Anuraeopsis, Polyartha, Trichocera, Keratella, Lecane, Asplanchna, and Filinia longiseta. In number, rotifers usually made up 80 to 90 percent of the zooplankton, ciliates comprised four to 15

percent and Crustacea, mostly Cyclops, about six percent. Frequently Cladocera were not present. Bosmina longirostris usually was the dominant cladoceran species.

Extensive sampling by R. Biswas (VLRP, 1971) at Ajena, Afram, Kpandu, Kete Krachi, Yeji, and Ampem from July to December, 1970, showed that maximum zooplankton numbers occurred at most places in October and November. This coincides with the phytoplankton peak. Yeji had the highest counts in August. Zooplankton was the most abundant at Kete Krachi (59/100 ml), Ampem (44.7/100 ml), and Ajena (28.6/100 ml). Proszynska (1969) first observed abrupt changes in zooplankton numbers and a lack of larval stages at Ajena in 1965 and suggested that the zooplankton may develop elsewhere to be carried into the Ajena area. Lawson et al. (1969) made similar comments.

Rajagopal (IAB, 1969) observed that total zooplankton increased four times overnight at Mpaha presumably as a result of currents. Proszynska (1967) studied the planktonic Crustacea of the Afram Confluence in 1966 and found that Crustacea were present all year, including abundant larval stages of Copepoda. She stated that these observations confirmed the suggestion that Crustacea occurring periodically at Ajena originate in the Afram Confluence. The idea of the shallow areas as nursery zones for zooplankton was suggested many years ago for Lake Erie and more recently for Green Bay, Lake Michigan.

Zooplankton made up slightly more than one percent of the food of fish (Lawson et al., 1969). It may be more important in shallow areas and little information is available on

planktonic Crustacea as food for larval and small juvenile fish.

Productivity and Trophic Conditions

The productivity of a lake is directly tied to the productivity of the drainage basin. Any long-term increase in productivity must be the consequence of a continually increasing nutrient supply such as has been the situation with many European and North American lakes undergoing accelerated eutrophication. There is little evidence to support the concept that natural eutrophication is the result of gradual accumulation of nutrients. On the contrary, what information we have on natural changes in lakes indicates some major change in the drainage basin resulting in changes in influx of nutrients and sediments. Also data on lakes receiving urban and agricultural wastewaters indicate that the rapid eutrophication is a consequence of continually increasing nutrient loading from sewage, agricultural fertilizers, and alteration of the drainage basin.

The nutrient-poor lateritic soils of Africa would not be expected to provide for high nutrient inputs to a lake via tributaries or direct run-off. As a result, lakes with nutrient-poor soils in general would be expected to be less productive than lakes lying in nutrient-rich soils. Of course, the morphometry of the basin is also important. Shallow lakes have a

faster recycling of available nutrients than deep lakes, because the productive euphotic zone is closely associated with nutrient release from sediments.

These same principles must apply to man-made lakes, but these relationships are usually obscured initially by disruption in the riverine ecosystem due to impoundment. It appears that for reservoirs in temperate regions it takes around 15 years for conditions to stabilize. The Volta Lake data indicate that in the tropics stabilization may occur much quicker.

The initial productivity of a man-made lake must be closely related to productivity of the flooded terrestrial environment and whether or not vegetation was cleared prior to flooding. Vegetation was not cleared from the Volta Lake Basin and this apparently determined the subsequent productivity and the nature of the production, i.e., the kinds of invertebrates and fish communities. Flooding of the terrestrial environment provided greatly increased food and spawning areas for those fish normally adapted to flood plains. Thus, initially, terrestrial vegetation was important in the food chain both for benthos and some fish. Second, the trees provided an extensive surface area for a luxuriant development of aufwuchs, i.e., attached micro-organisms. It appears that the main food chain and the economy of the lake has been aufwuchs based. Some fish feed directly on the aufwuchs while others feed on invertebrates, primarily the mayfly Povilla, which feed on the aufwuchs.

Evidently rapid decay in tropical regions will quickly eliminate the softwood trees such as the silk cottons favored by the Povilla for burrowing. It is predicted that the hardwood trees will remain for many years. Nevertheless, the surface area for aufwuchs will be reduced by loss of the softwoods and as a consequence plankton will assume greater relative importance in the food chain and planktivorous fishes, e.g., Tilapia, and clupeids also should become more important. The nutrients in the lake and nutrient inputs to the lake are low and therefore plankton crops have been low, except for some blooms in the shallow arms. Consequently, with the lake's economy based to an increasingly greater extent on plankton, a further decrease in fish production can be anticipated.

It can be reasonably assumed that other man-made lakes in the tropics will initially be productive because of the flooded terrestrial vegetation. All of this organic matter may not be cycled through a food chain useful to man, however; especially if the lake is deep, it stratifies, and anaerobic conditions develop in the bottom waters. Flooded trees and other vegetation will provide extensive areas for aufwuchs as well as hiding places from predators for fish. Eventually plankton will become increasingly important depending on the nutrient supply and rate of recycling as a function of depth, stratification, and exchange with the sediments.

The decrease in phosphorus, increase in transparency and decrease in phytoplankton tend to throw doubt on Biswas' (1970) statement, "The organic matter derived from decayed phytoplankton also led to a gradual eutrophication of the lake." Furthermore, the lake is too large to be showing signs of rapid eutrophication in such a short time due to the accumulation of plankton, especially in view of the low plankton concentrations.

The productivity of Volta Lake, as with other lakes, must depend on the availability of nutrients and accessory growth substances, quantity and quality of light, temperature, and turbulence. Light penetration apparently varies relatively little from place to place (Viner, 1969a). Temperatures are uniformly high. Consequently, these appear not to be major controlling factors.

In view of the decreasing nutrient supply and the obvious response of algae to nutrient inputs in the rainy season inflow, attention should be directed to the availability of nutrients and mixing processes.

The following considerations should be addressed with regard to availability of nutrients:

1) Are the major nutrients and accessory growth substance in chemical forms which can be used by the algae? Measurements of phosphorus, silicon, etc., may not indicate what is available.

2) Is bacterial activity such that it effectively facilitates recycling to the plants? Aerobes are more efficient than anaerobes, and this is an important consideration in lakes with an extensive oxygen deficit in the hypolimnion.

3) What is the importance of allochthonous material, i.e., material brought into the lake? Data for Volta Lake indicate that these materials formed the base of the food chain as the basin was flooded. The importance of this will decrease as the flooded terrestrial vegetation decays. This is already indicated for Volta Lake by a decrease in benthic biomass. The extent to which the terrestrial environment will contribute to lake productivity remains to be established, especially in view of the fluctuations in water level which will alternatively expose and reflood approximately 800 sq. km.

4) Nutrient supply--what is the nutrient budget for Volta Lake? Each of the following must be considered: contributions from tributaries; contributions from direct run-off; contributions from precipitation, which has been overlooked and may be very important (for example, Viner [1969b] reported that 300-1000μg/l of PO_4 and 1000-2000μg/l of total N were found in the

rainwater of Lake George); loss of nutrients by outflow; loss of nutrients to the sediments; and amount returned from the sediments.

Proposed Kinds of Research

Several kinds of research--some short-term and long-term to obtain additional data--and examination of problems for which much of the data are available, could be undertaken which would supply inputs to several models useful for understanding Volta Lake and perhaps have wider application to future tropical man-made lakes.

1) Nutrient budget.—In order to obtain data for such a model, answers are needed to the questions on nutrient availability set forth in the preceding section. To obtain at least a first approximation, information is needed on inflow and nutrient content of inflow. Data should be obtained on nutrients in the rainfall to relate this information to rainfall records. Nutrients in the outflow should be measured at the dam and calculations made related to flow. Exchange between sediments and the water present the most difficult task and net loss to the sediments may be estimated by difference from the other data.

2) Primary productivity.—Measurements should be made for the major arms and the open water of Volta Lake. If annual or monthly average values can be related to flushing rates of the arms and magnitude of exchange between arms and open water, then there is a good basis for determining the importance of the various arms to the open lake and to the overall productivity of the lake.

3) Flushing rate model.—On the basis of river flow, concentration of some conservative ion, or conductivity in river water and its distribution in the arm, it will be possible to calculate the flushing rate (i.e., the time it takes a one-day accumulation of river water to move through the arm), the rate of lakeward flow through any section of the arm, and the magnitude of the counter-current moving into the arm from the lake. As indicated above, such information could be used to develop a productivity model. The following papers present the flushing model: Beeton _et al_., 1967; Modlin and Beeton, 1970.

4) Stability of stratification and vertical mixing.—Bretschko (1971) prepared a report, "Instructions for Calculating Stability with Special Reference to Lake Volta." It should be possible to predict the degree of

stratification and mixing using Bretschko's method and including information on wind direction and force, fetch, and anticipated thermal conditions. Such information would be especially pertinent for predicting development of an anaerobic hypolimnion, and possible meromixis.

6. Aquatic Weeds in Volta Lake and Their Control

Introduction

Ever since the explosive growth of the aquatic fern, *Salvinia*, on the man-made lake at Kariba, the development of aquatic weeds has been a topic of considerable interest to those contemplating the construction of large reservoirs in Africa. Pierce (1971) pointed out that in Ghana, officials and many citizens were concerned about the possible rapid development of such weeds on Volta Lake. Their concern was justified, since several conditions conducive to rapid growth of aquatic weeds would be present in the new lake. In general, the necessary conditions are:

1) presence of aquatic weed species in the area,
2) lack of natural predators of the weed species,
3) plant nutrients available in excess,
4) protection from wind and wave action,
5) flat terrain which leads to shallow water.

In regard to the first condition, a preliminary survey of aquatic weeds in the Volta River Basin by Lawson (1963) indicated many weeds were present, but certain well-known aggressive tropical weeds were absent. For example, papyrus (*Cyperus*

papyrus), water hyacinth (Eichhornia crassipes), Kariba weed (Salvinia molesta, formerly S. auriculata), and alligator weed (Alternanthera philoxeroides), although present elsewhere in Africa, were fortunately missing from the river basin. But, still 151 species were found and natural controls were probably absent for some of these.

Excess plant nutrients could be expected in Volta Lake if the existing forest and savannah vegetation were cleared or burnt before flooding. It was decided, however, not to clear the vegetation prior to dam closure, and consequently, the release of plant nutrients from decomposition would be more gradual. But some excess mineral salts would be leached from flooded forest and farm soil. Also, since no clearing was carried out, the inundated trees and shrubs wherever exposed would provide protection against wind and wave action during the lake filling. This would be especially true in the shallow regions which would occur because of the flat terrain in many areas.

The potential existed then for aquatic weed development at Volta Lake. What eventually happened is an interesting and informative story, which rivals the Kariba experience as a lesson of what to expect when man-made lakes are formed in Africa.

Objectives

This report is not intended to be a complete review or a critical analysis of the work done on the vegetation of Volta Lake. It is written with the intention of providing aquatic biologists, hydrologists, and planners of future dams with a recent view of what has happened with the aquatic weeds on the lake.

This was written after reading much of the literature regarding aquatic weeds at Volta Lake, and after a few visits to selected areas. The objectives of this report are to summarize and comment on:

a) the succession of the aquatic vegetation on the lake,
b) weed problems which have developed,
c) beneficial aspects of the weeds,
d) weed control measures past and present,
e) cost of control,
f) possible directions for future control programs.

Plant Succession on Volta Lake

Pre-impoundment.--Before the dam was closed in 1964, Lawson compiled a check-list of aquatic weeds in the Volta Riv Basin (Lawson, 1963). He found 151 species, covering a wide range of submerged, floating, and emergent (shoreline) aquatic A list of the aquatic communities in the lagoons off the river

(Table 3) illustrates the general nature of this flora. In the main river bed itself very few aquatics occurred because of annual scouring (Hall and Pople, 1968).

TABLE 3. Weed Communities in Riverine Lagoons Before Impoundment[a]

Community	Above Dam Site	Below Dam Site
Emergent	Vossia cuspidata Ludwigia sp. Polygonum tomentosum Echinochloa pyramidalis	Vossia cuspidata Ludwigia repens Polygonum spp. Scirpus cubensis Neptunia oleracea
Floating	Nymphaea sp. Pistia stratiotes Duckweeds (Lemna, Azolla, Salvinia)	
Submerged	Ceratophyllum demersum Utricularia sp.	Ceratophyllum demersum

[a]Source: Lawson, 1963.

Post-impoundment, early stages.--Lawson (1967) and Hall *et al*. (1969) described the early aquatic weed development on the new lake. In one arm of the lake the formation of *Vossia* sudd was noted. Although *Vossia* sudd had previously been found in the lagoon areas off the original river, it was a disturbing development. The term "sudd" derives from the Arabic word ("sadd") for "block." This calls to mind large floating masses of papyrus sudd which are capable of blocking passage on the White Nile or creating shipping hazards on Lake Victoria (Thompson and Gaudet, 1973). In general terms, sudd may be

defined as a compact mass of floating plant material usually dominated by one species. It is exemplified by papyrus sudd in many areas of Africa, Eichhornia sudd on the Nile (Gay, 1958), Salvinia sudd on Lake Kariba, Rhodesia and Zambia (Boughey, 1963), Echinchloa sudd on Kainji Lake (El Din el Zarka, 1970), and Vossia sudd on Lake Bangweulu in Zambia (Wild, 1961). Sudd tends to break apart at its edges and floating sudd islands are thus released which can spread one or more weed species to new areas.

On Volta Lake the Vossia sudd consists of several aquatic species (Table 4) dominated by the large aquatic grass, Vossia cuspidata. Islands produced at the edges of the sudd tended to lodge in the crowns of the inundated trees.

TABLE 4. Comparison of Species Composition of Sudd on Lake Volta[a]

Community	Vossia Sudd	Scirpus Sudd
Emergent grasses & sedges	Vossia cuspidata Leersia Hexandra Oryza longistaminata Fuirena stricta	Scirpus cubensis Paspalum conjugatum Digitaria horizontalis Cyperus spp.
Emergent herbs	Ipomoea aquatica Ludwigia leptocarpa Ludwigia stolonifera	Ludwigia leptocarpa Sphenoclea zeylanica
Floating	Pistia stratiotes Salvinia nymphellula	
Submerged	Ceratophyllum demersum Utricularia inflexa	

[a]Source: Lawson, 1967.

In addition, another type of sudd, Scirpus (Table 4), became established near dead logs closer to shore.

The formation of sudd was distressing, since sudd formation might cover many of the shallow bays in the new lake and cause innumerable problems, as it did on Lake Kariba. Fortunately, this situation did not materialize. Possibly a lower level of nutrients (but most likely wind, waves, or other factors) prevented the sudd from growing and consolidating. The exact reason for this remains unknown. Now (1973) an occasional small sudd island is seen floating on the lake or washed ashore. Scirpus sudd is relegated to only a few protected areas, and Vossia, although spreading to many places along the shore, does not form sudd in any significant quantities.

Post-impoundment, later stages.--As the lake filled and the flora changed, some species became more or less common. The earlier list of aquatics (Hall et al., 1969) had been superceded by a more comprehensive list (Hall et al., 1971) which includes 198 species recorded from the lake area. The largest portion of these are the flood-tolerant species common to the exposed mud of the drawdown area. The most prominent species are illustrated and described in this last work. Table 5 lists the species of the drawdown zone, including the emergents which survive the rising water during flood. Other macrophytes on the lake are listed in Appendix III.

TABLE 5. Drawdown Zone Plant Species on Volta Lake[a]

Emergents	Drawdown Area
Alternanthera sessilis	Alternanthera sessilis
Neptunia oleracea	Glinus oppositifolius
Typha australis	Ludwigia erecta
Cyperus articulatus	Polygonum senegalense
Eclipta prostrata	Andropogon gayanus
Polygonum senegalense	Echinochloa pyramidalis
Phragmites karka	Leptochloa caerulescens
Cyperus sphacelatus	Schizachyrium sanguineum
Mimosa pigra	Cyperus distans
Thalia welwitschii	Torulinium odoratum
Sacciolepis africana	Eclipta protrata
Fimbristylis dichotoma	Heliotropium indicum
	Ludwigia hyssopifolia
	Sphenoclea zeylanica
	Brachiaria mutica
	Imperata cylindrica
	Oryza longistaminata
	Sorghum arundinaceum
	Cyperus sphacelatus
	Etulia conyzoides
	Indigofers paniculata
	Mitragyna inermis
	Tephrosia platycarpa
	Echinochloa stagnina
	Leersia hexandra
	Paspalum orbiculare
	Vossia cuspidata
	Fimbristylis dichotoma

[a]Source: Hall *et al.*, 1971.

Present Aquatic Flora

Emergents.--Many of the emergent species which are part of the present flora on Volta Lake are typical of swamp and emergent lake vegetation in Africa (Table 6). The most notorious African emergent, papyrus, is missing from the Volta Lake flora. *Vossia* has become the most common emergent especially on the wind-swept shores facing north and east, which is the direction of the prevailing winds (Pierce, 1971).

Vossia is the most competitive emergent on the lake. This is also true of *Vossia* in other areas of Africa. Along the Nile *Vossia* (locally known as "um soof") experiences annual flooding similar to the annual drawdown on Volta Lake. On the Nile the emergents can be divided into two categories depending on their ability to withstand flooding (Table 7). The relatively more strongly rooted species, such as *Oryza*, *E. pyramidalis*, and *Phragmites*, are found in areas where the depth of maximum flooding is less than 200 cm. The relatively more weakly rooted grass species, *Vossia* and *E. stagnina*, and the sedge, papyrus, are found in areas where the maximum depth is higher than 200 cm. In addition to depth, the maximum number of days of flooding also seems correlated with the distribution of these emergents (Table 7). It has also been noted on the Nile (Anon., 1954) that *Vossia* is better able to withstand wind and wave action than other emergents. It typically grows in stretches of the river where the water is swiftly

TABLE 6. Comparative List of Common Emergent Aquatic Plants Found in African Swamps and Lake Edges

White Nile Sudan[a]	Lake Chad Chad[b]	Okavango Swamp Botswana[c]	Volta Lake Ghana[d]
Tall Rhizomatous Emergents			
Vossia cuspidata	Vossia cuspidata	Vossia cuspidata	Vossia cuspidata
Echinochloa stagnina	Echinochloa stagnina	Echinochloa stagnina	Echinochloa stagnina
E. pyramidalis	E. pyramidalis	E. pyramidalis	E. pyramidalis
Oryza longistaminata		Oryza longistaminata	Oryza longistaminata
Typha capensis	Typha australis	Typha capensis	Typha australis
Phragmites communis	Phragmites australis	Phragmites australis	Phragmites karka
		Miscanthidium junceum	
Smaller Emergents			
Ipomoea aquatica	Ipomoea aquatica	Ipomoea rubens	Ipomoea aquatica
Thelypteris striata	Thelypteris totta	Thelypteris totta	Thelypteris striata
Leersia hexandra	Leersia hexandra	Leersia hexandra	Leersia hexandra
	Scirpus cubensis	Scirpus cubensis	Scirpus cubensis
	Polygonum spp.	Polygonum senegalensis	Polygonum senegalensis
Cyperus spp.		Cyperus spp.	Cyperus spp.
Ludwigia stolonifera	Ludwigia stolonifera	Ludwigia stolonifera	Ludwigia stolonifera
		Ludwigia leptocarpa	Ludwigia leptocarpa

[a]Anonymous, 1954.

[b]Leonard, 1969.

[c]Lee, pers. comm.

[d]Hall, *et al.*, 1971.

flowing. On the Congo River and in Lake Tumba, Zaire, Vossia does very well in sheltered bays or on shores exposed to wind and waves (Gaudet, pers. obs.).

TABLE 7. Depth and Duration of Flooding of Different Species in the Nile Swamps[a]

Species	Depth of Flooding (cm)		Duration of Flooding (days)	
	Max.	Aver.	Max.	Aver.
Cyperus papyrus	265	181	300	175
Vossia cuspidata	280	180	263	172
Echinochloa stagnina	252	191	230	167
Oryza longistaminata	162	110	215	135
Echinochloa pyramidalis	190	87	213	20
Phragmites communis	186	146	150	20

[a]Source: Anonymous, 1954.

Pierce made several points which bear on Vossia's competitive success. First, there is a large difference in mode of reproduction among the emergents. Vossia reproduces mostly by vegetative propagation while the others, e.g., Polygonum, reproduce by seed. Quite often it is possible to see Vossia overgrowing young Polygonum plants. Thus, Vossia's rapid vegetative growth may be another important factor, especially since it can grow continuously throughout the year. During flood periods Vossia does well by sending out new shoots over the water. As the water recedes Vossia is stranded, while Polygonum and other herbaceous emergents, such as Alternanthera, and Ludwigia, grow

up rapidly from seed on the exposed mud. But eventually Polygonum will in its turn succeed when flooding again occurs, since Alternanthera and Ludwigia do not tolerate flooding as well as Polygonum. Here it seems that hollow stems of Polygonum and Vossia are more adapted to flotation. Alternanthera and Ludwigia can float, but to do so they require specialized tissue (acrenchyma) which possibly requires some time to develop. Although both Polygonum and Vossia are tolerant of flooding, when the two plants occur in a given area, Polygonum is at a disadvantage. The burrowing mayfly (Povilla adusta) attacks its soft hollow stems (Pierce found 0.12 larvae/cm of stem) to the point that some populations of the plant have been decimated. A few larvae are found in Vossia, but its tough stem makes it more resistant to such insects.

It would seem then that Vossia in other parts of Africa is a pioneer emergent that has become more and more widespread. On Volta Lake Vossia is more successful than most emergents (Pierce, 1971). In the Perennial Grass-Polygonum Zone (Table 8 and Fig. 3) Vossia dominates the outer edge toward the lake, while Echinochloa spp. and Oryza are relegated to the inside (Pierce, 1971). The question arises as to how Vossia comes to dominate this zone, but Pierce (pers. comm.) judges that this zonation will disapper in time.

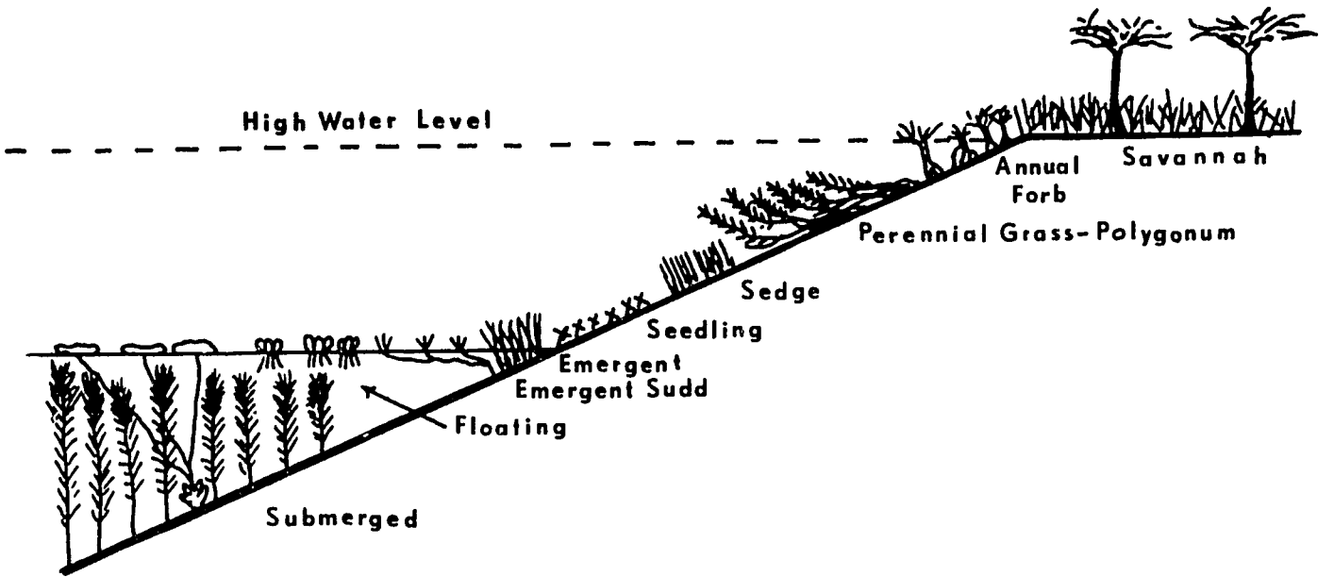

Figure 3. Plant zonation on Volta Lake.

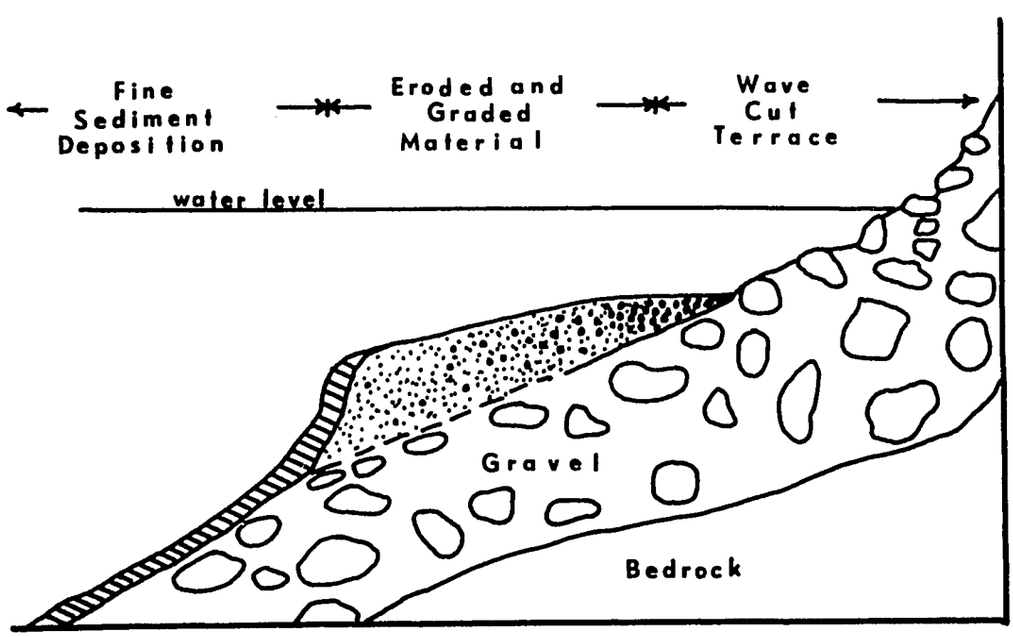

Figure 4 Erosion of a lake shore.

TABLE 8. Generalized Plant Zonation on Volta Lake[a]

Zone	Area	Habitat	Typical Plant(s)
Savannah	dry land	not flooded	terrestrial grasses, etc.
Annual Forb	drawdown	exposed 35-45 weeks	Indigophora, Tephrosia
Perrenial Grass-Polygonum	drawdown	exposed 10-35 weeks	Vossia, Echinochloa, etc. stranded at low water
Sedge	drawdown	exposed 10 weeks	Fimbristylis, Cyperus
Seedling	just above lake edge	wet mud	Alternanthera, and Polygonum seedlings
Emergent	lake edge	shallow water	emergent species
Emergent Sudd	lake edge	shallow water	sudd species
Floating	open water	just off-shore	water lilies (Nymphaea), duckweed, Pistia
Submerged	open water	0.1 - 3.0 cm depth	Ceratophyllum

[a]Source: Pierce, 1971; Hall, 1970.

In summary, because of its weak rooting and ability to withstand flooding; its stem which provides flotation and protection from insects; its rapid, continuous growth, vegetative reproduction, and spread by floating sudd island; its tolerance to wave action and ability to grow on sandy soil; Vossia is almost a perfect weed species. If one also considers its resistance to herbicides and its production of needle-like hairs

at its leaf sheath, which discourage control by grazing and make handcutting difficult, it is not surprising that weed biologists regard Vossia as a weed of some importance in Africa.

The floating vegetation.--Other than the previously mentioned works on sudd formation, the only other work is that of Attionu (1970). He found Pistia to be quite efficient in taking up nutrients. For example, after three days, two medium-sized rosettes had depleted a nutrient solution of K by 95 percent, Na by 18 percent, Ca by 37 percent, N by 53 percent, and P by 31 percent. In nature Pistia mats must accumulate large amounts of nutrients. If the nutrient in the substrate is increased, Pistia produces new rosettes and leaves, but vegetative growth of the whole plant is discouraged. In other words, increased nutrients encouraged reproduction of the plant. Attionu noted that optimum production could be achieved by Pistia in two ways: (a) increase in average size of the whole plant, or (b) increase in production of new rosettes. Thus, in crowded mats close to shore in the presence of high levels of nutrients (typical of inshore water), production is increased by producing rosettes. In offshore waters with less crowding and less nutrients, the plants increase in size. Such an increase in size would be an advantage when the plants are eventually stranded during the dry season, because these larger plants are more resistant to desiccation.

It should be pointed out here that in other tropical lakes, drawdown is known to favor the spread of floating

vegetation. For example, Hestand and Carter (1973) found that drawdown in Lake Ocklawaha in Florida (USA) resulted in a decrease in submerged, rooted aquatics, such as Ceratophyllum demersum. This was due to several factors; obviously drying out of the hydrosoil after drawdown was effective, but also the rapid increase in depth and the increased turbidity after reflooding had an adverse effect. In this lake after reflooding, only those aquatic weeds adapted to flotation--the free-floating water hyacinth (Eichhornia), floating-leaved water lily (Nuphar)--and the hollow-stemmed, flood-tolerant emergent, alligator weed (Alternanthera), have survived and done well. On Volta Lake a similar but less dramatic effect is noted with Vossia.

The submerged vegetation.--The succession of submerged plant life in Volta Lake has resulted in one dominant plant, Ceratophyllum. The only other obvious submerged plant is Utricularia, which is found in isolated patches in sheltered areas. Several other submerged species may be expected to appear in the lake as more benthic habitats develop. Below the dam, in the Volta River, two submerged weeds, Potamogeton octandrus and Vallisneria aethiopica, are now very common. Recently this Potamogeton has been found just above the dam (Odei and Opoku, pers. comm.). The appearance of the genus is hardly surprising since, like Ceratophyllum, it is common to many aquatic habitats throughout the world. Potamogeton is common in other man-made lakes such as Lake Kariba (Mitchell, 1969)

and Lake Nasser (Anonymous, 1972). Possibly Vallisneria may follow as the next introduction, but this will not happen until a suitable habitat develops. Such a habitat seems to be developing along the wave-swept shores where a sandy substrate is becoming more common. It has been known for some time (Wilson, 1941) that Ceratophyllum communities prefer fine sediments while Vallisneria dominates sandy substrates exposed to severe wave action. Hall and Pople (1968) predicted that sandy soil with moderate wave action might develop in the lake and both Potamogeton and Vallisneria might become established, but they felt the annual fluctuation in lake level might adversely affect them. Pierce (pers. comm.) concurs that unstable water level is a limiting factor.

The drawdown area.--The drawdown area on Volta Lake is that area of the lake immediately below high water level that is exposed by the annual fluctuation in lake level (Anonymous, 1971a). Drawdown usually occurs from October to July when evaporation, spilling and consumption of water for power generation exceed inflow and rainfall. Approximately 80,000 hectares are exposed by drawdown. The drawdown flora is composed of water-loving species which develop each year on this exposed soil. When flooding again occurs, the species composition may be affected so that when the area is then uncovered by drawdown, the flora that does develop may be quite different. This is illustrated in Table 9, using data obtained by Hall (1970) on a plot in the Perennial Grass-Polygonum Zone.

TABLE 9. Effect of Flooding on Some Drawdown Species in a 900 m^2 Plot[a]

Species	Family	Habit	Frequency[b] July 1968	Frequency[b] July 1969[c]
Borreria scabra	Rubiaceae	Creeper	83	0
Tridax procumbens	Compositae	Herb	61	0
Sorghastrum bipennatum	Graminae	Grass	53	0
Andropogon gayanus	Graminae	Grass	41	3
Polygonum senegalense	Polygonaceae	Herb	0	89
Alternanthera sessilis	Amaranthaceae	Herb	0	69
Ludwigia hyssopifolia	Onagraceae	Herb	0	52
Fimbristylis dichotoma	Cyperaceae	Sedge	0	47
Heliotropium indicum	Boraginaceae	Herb	0	44
Scoparia dulcis	Scrophulariaceae	Herb	0	42
Glinus oppositifolius	Molluginaceae	Creeper	0	32

[a]Source: Hall, 1970.

[b]Percent occurrence in plot, e.g., 50 indicates that a species was found throughout one-half the plot.

[c]After flooding in August-September, 1968.

This shows the development of species characteristic of the Perennial Grass-Polygonum Zone. Flooding brings about changes in most of the zones listed in Table 8 except the Savannah Zone. This lies just outside the flooded area. Some grasses of this zone may be stimulated by the increased availability of water, but most are unaffected. The Emergent and Emergent Sudd Zones fluctuate greatly since at high water (Fig. 3) the plants of the Perennial Grass-Polygonum Zone are then considered emergents (rooted) and emergent sudd (floating mats). At low water these are left stranded and the Emergent Zone then contains very few species.

Lake Volta Compared
to Lake Kariba

It is interesting to compare the major changes in the succession of aquatic weeds in Volta Lake with the succession in Lake Kariba during the first ten years of their existence (Table 10). In Kariba, the "sudd phase" lasted longer, showed a decrease eventually, but still persists in large quantity. The drawdown flora has taken longer to develop (possibly because of the steeper shoreline) and the submerged flora is still developing. It is also of interest to note the development of a sudd phase in a third man-made African lake, Kainji Lake, in Nigeria. In Kainji Lake during the first few years of filling, small amounts of Echinochloa sudd have been noted in the northern part of the lake. This sudd is made up of E. stagnina, Polygonum senegalense, Ludwigia stolonifera, Pistia stratiotes and Utricularia inflexa (El Din el Zarka, 1970). As far as can be determined, this sudd has not become troublesome on this lake, and it is possible that this will be of little consequence in future years.

On Volta Lake the vegetation is still undergoing changes, and it will be difficult to predict which species will predominate in years to come. It is likely, however that Vossia will become a major factor in the evolution of the emergent flora. Pistia and other floating plants seem unable to develop in the face of increasing exposure to wind, turbulence, wave action and natural predation. On the other hand,

new submerged types may arrive and do quite well on the sandy wave-swept shores.

TABLE 10. Comparison of Major Changes in Aquatic Weeds During the First 10 Years in Two African Man-Made Lakes[a]

Year	Lake Kariba	Volta Lake
1	Dam closed (1959)	Dam closed (1964)
2	Sudd development	Sudd development
3	Increase in *Ceratophyllum*	Increase in *Ceratophyllum*
4	Sudd increases	Decrease in sudd
5		Development of grasses, sedges, herbs in drawdown
6	Decrease in sudd, *Potamogeton* appears	Spread of grasses, sedges & herbs in drawdown area
7	Development of grasses, sedges, herbs in drawdown area	*Vossia* and *Polygonum* increase
8		*Vossia* continues increase; *Polygonum* stabilizes
9	No dramatic changes	No dramatic changes
10	New submerged plant (*Lagerosiphon*) appears	New submerged plant (*Potamogeton*) appears

[a]Source: Mitchell, 1969; Pierce, 1971.

It is not far-fetched to speculate that the Volta Lake flora is following a course of succession that is not very much different from what has developed in aquatic habitats in other parts of Africa.

Weed Problems

Substrate for bilharzia snails.--The change from a river to a lake environment has resulted in an increase in snail habitats. This increase in snail habitats, coupled with a larger

number of humans having access to the shoreline has resulted in a rise in the snail-borne disease, bilharziasis (schistosomiasis). The debilitating nature of this disease makes it one of the most serious public health problems in the tropics today, with 74 million infected people in Africa alone (Wright, 1968). In addition to human suffering and deaths caused by bilharziasis, the economic losses are enormous. It is estimated to have caused a decrease in production of 33 percent in Egypt. This represents an annual economic loss of 560 million dollars (Faroq, 1967).

Before Volta Lake filled, Paperna (1969) noted that Bulinus truncatus rohlfsi (the snail vector of Schistosoma haematobium, causal agent of urinary bilharziasis) was quite common in the lagoons off the main river. After lake filling, an increase in the number of these snails followed and seemed related to the increase in aquatic weeds. Later (1967-68), with a decline in sudd, the snail populations decreased. Paperna attributed this to a change in habitat. With a decline in sudd, Bulinus sought out stones, detritus, and the Ceratophyllum beds which had developed. Paperna (1969) and Odei (1973) have shown that these snails are more abundant in Ceratophyllum than in any other substrates in Volta Lake (Table 11).

TABLE 11. Distribution of Bulinus Snails on Substrates Sampled over 24 Months on Volta Lake[a]

Substrate	No. of Snails	% of Total
Ceratophyllum	280	48
Old fish traps	127	22
Wood, logs, twigs	82	14
Polygonum, flooded	46	8
Pistia	30	5
Lake bottom	20	3

[a]Source: Odei, 1973.

The host snails will grow on emergent weeds such as Vossia, Polygonum, Alternanthera, and Ludwigia, but these weeds are exposed during the drawdown and many Bulinus snails are left stranded (Odei found 148 dead snails inside a 9 m^2 section of the drawdown area), but as drawdown is occurring some snails retreat to deeper water and take refuge in Ceratophyllum beds. Odei found host snails on Ceratophyllum dredged up from 4 m, well below the depth exposed by drawdown (ca. 3 m). Floating plants also serve as substrate, but in different ways. For example, water lily leaves (Nymphaea) support very few snails or their eggs, possibly because they are easily attacked by predators on the underside of these large leaves. Pistia and Salvinia support a moderate number, but the duckweed, Spirodela, serves only as a depository for eggs and as a nursery. These tiny plants are too small to support adult snails but will support younger specimens. As the eggs hatch out, the juvenile snails browse on the soft leaves and are thus transported with the floating plant to new sites where substrate for adult snails may be suitable.

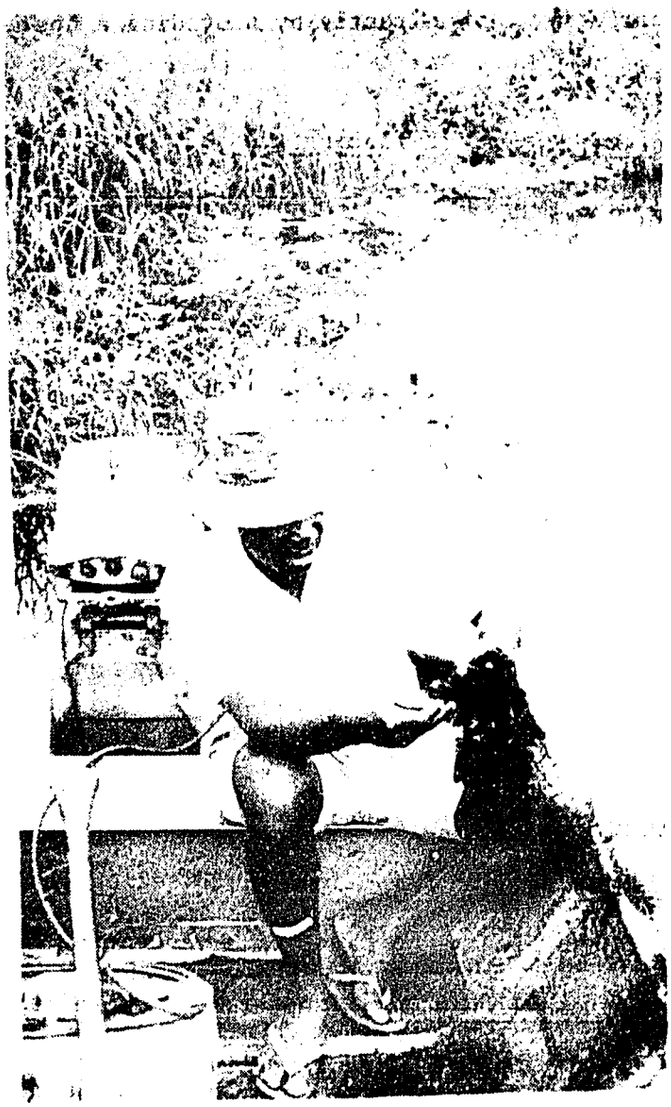

Fig. 5. Aquatic weed growth near Ampem (August). The Ceratophyllum weed held in this VLRP researcher's hand is a dominant submerged weed of Volta Lake. Bulinus snails are numerous in this weed. Fishermen commonly dive to set traps for Tilapia and other species in such weed-infested embayments, and are consequently exposed to schistosomiasis infestation.

By and large the most important weed substrate in Volta Lake is Ceratophyllum. It serves as a reservoir for Bulinus during low water. It provides: (a) substrate for attachment and oviposition, (b) protection from predators and intense sunlight, and (c) a source

of food, directly, or indirectly by providing a host of "aufwuchs" or periphyton.

Interference with fishing and transport.--Pierce (1971) on several field surveys recorded the complaints of fishermen that the emergent and floating weeds interfered with their inshore fishing activities. And in some cases, small fishing villages were ignored by transport launches because of heavy growths of emergent weeds in front of the landing area. This necessitated a considerable overland trip to carry fish and farm produce to markets. The Ceratophyllum beds in front of some fishing villages have become too difficult to penetrate even with a light outboard motor (Gaudet, pers. obs.).

Beneficial Aspects of the Weeds

Fishing.--The observations by Loiselle (Table 12) indicate that Vossia beds are a more productive vegetative habitat for fishing than Ceratophyllum beds, sedge or bare shoreline. Loiselle felt that the depauperate fish fauna in Ceratophyllum beds may be due to the fact that only a few specialized fish are capable of withstanding the conditions in such a specialized habitat.

As pointed out by Petr (1971) the burrowing mayfly, Povilla, forms an important item in the diet of Volta Lake fish. But eventually, a decline in Povilla is expected when the inundated softwood trees and emergents such as Polygonum become in short supply. At that time the periphyton which develops in Vossia mats and on other aquatics will likely become an increasingly important supply of fish food.

TABLE 12. Comparison of Fish in Different Littoral Habitats[a]

Habitats	Stations Sampled	Biomass (kg/ha)	No. of Species	Dominant Group
Vossia beds	7	255	38	Cichlidae
Ceratophyllum beds	2	156	19	Polpteridae
Sedge, mixed grass beds	4	63	40	Cichlidae
Bare shoreline	9	175	28	Bagridae

[a]Source: Loiselle, 1972.

Nutrient cycling.--On Lake Kariba the aquatic vegetation was thought to act as a sump for nutrients, i.e., mats of *Salvinia* would take up quantities of nutrients which would otherwise be lost from the lake by outflow (Bowmaker, 1970). On Volta Lake the aquatic vegetation traps only a small portion of nutrients present in such a large lake. Compared to the nutrients lost to the river below the dam, however, the nutrients trapped by the aquatic weeds represent a considerable "savings" especially in iron, nitrogen, and phosphorus (Tables 13, 14).

Much of this nutrient is present in the emergent weeds, which take most of their nutrient from the hydrosoil, rather than directly from the water. But periodic flooding allows some replacement of nutrients from the flood water itself. Thus, emergent weeds recycle nutrients such as iron, nitrogen and phosphorus which normally would be trapped in mud and silt. These emergents were assumed to cover a strip

TABLE 13. Estimate of Nutrients Trapped in Aquatic Weeds on Volta Lake[a]

Nutrient (% D.W.)	Submerged *Ceratophyllum demersum*[b]	Floating *Pistia stratiotes*[c]	Emergent *Polygonum* spp.[d]	Total Trapped (kg x 10^3)	%
N	2.49	3.27	1.20	4821	30.9
P	0.20	0.31	0.15[e]	591	3.7
K	3.00[e]	5.48	1.16	4735	30.4
Na	0.60[e]	0.61	0.04	212	1.3
Ca	2.60	3.80	0.26	1260	8.0
Mg	1.10	0.54[e]	0.12	558	3.5
Fe	0.10[e]	0.11[e]	0.89	3392	21.7
Biomass (kg DW/m^2)	0.666	0.474	0.760[f]		
Area covered[g] (estimate) (m^2)	13 x 10^6	2.5 x 10^6	500 x 10^6		
Total biomass (kg DW)	87 x 10^5	12 x 10^5	3800 x 10^5		

[a]Source: Appendix I, attached--notes on calculations.

[b]Boyd, 1970.

[c]Attionu, 1970 aver.

[d]Lind and Visser, 1972.

[e]Estimates based on data of Denton, 1965, for similar tropical aquatics.

[f]Hall, 1970.

[g]See calculation in Appendix I.

100 m wide around the lake edge, essentially comprised of the drawdown flora. The amount of iron, nitrogen and phosphorus recycled each year by the lake flora is quite significant.

TABLE 14. Nutrients Lost in Outflow from Volta Lake

Nutrient	Surface water 1969[a]	(mg/l) 1971[b]	Average (mg/l)	Amount lost anually[c] (kg x 10^3)
N	-	0.15	0.15	336
P	-	0.002	0.002	4
K	5.07	2.8	3.9	9733
Na	3.76	3.5	3.7	8286
Ca	7.82	7.0	7.4	16571
Mg	2.06	4.1	3.1	6942
Fe	0.019	0.05	0.03	67

[a]Entz, 1969.

[b]Czernin-Chudenitz, 1971.

[c]Based on an outflow at the generating plant of 7.1 x 10^5 l/sec (Anonymous, 1971b).

Trapping of sediments.--The drawdown area is now being tilled since it is considered prime agricultural land. As tilling continues to expand, the soil in this area will become less compact and more easily acted on by waves. Wave action has a tendency to sort out and remove finer sediments (Fig. 4) and to wash out the organic matter, leaving a sandy gravelly terrace. Some of these effects on the lake are now being observed by agronomists (Tsangarakis, pers. comm.).

Emergent vegetation, especially reed swamps, is very efficient at trapping sediments (Gaudet, 1973); possibly Vossia will be of some use in this way. It is already being used to replace the organic content of this soil, since some farmers plow burnt Vossia back into the wave-washed soil.

Composting.--Since the emergent vegetation of the lake recycles significant amounts of nutrients, especially phosphorus, nitrogen and iron, use as compost has a potential. If these weeds are cut and left in place, they would wash out with the annual flood and the nutrients would be returned to the lake after decomposition of the lake bottom. On the other hand, if used for compost, the nutrients would be further cycled in the drawdown system before being returned to the lake. In a way, this has been the goal of many workers for many years. How many times has the question been asked: "Why can't these weeds be used in agriculture? What a waste of good nutrients!" The use of aquatic weeds such as Eichhornia in the tea plantations and other crops in India has been advised and practiced for some time (Anonymous, 1966). The same practice has been proposed in the southern U.S.A. where aquatic weed infestations are notorious.

One obstacle to composting schemes is the transport of heavy, wet, bulky weeds to areas in need of green manure or compost. On Volta Lake transportation problems are not present, since the emergent aquatic weed is left stranded on the exposed mud of the drawdown area, which is later cultivated.

The use of submerged weeds for compost will be more difficult, although the practice is not unknown. In the shallow lakes of Kashmir (e.g., Dal Lake near Srinagar) many Kashmiri farmers harvest submerged weeds in canoes for use as green manure (Gaudet, pers. obs.).

At present on Volta Lake field trials and experiments are underway using aquatic weeds such as Vossia and Polygonum from the drawdown as green manure and crude compost. The usual practice is to burn Vossia first, to make it more manageable, then to work it into the soil. This results in an immediate increase in soil organic matter, since the drawdown soils generally consist of highly permeable sandy loams with low organic matter, averaging 1.25 percent in the top 15 cm (Amatekpar, 1970). These trials may suggest an important and possibly necessary step in drawdown agriculture.

Grazing.--As drawdown agriculture around the lake increases, the number of grazing animals may also increase. At present near Ampem, sheep graze in and near the drawdown area, or uncleared plots of stranded aquatic weeds. Certain aquatic weeds are known to be used for grazing cattle, e.g., along the Nile the grass, Echinochloa stagnina, is readily eaten by cattle. Table 15 shows its crude composition compared to Vossia. Vossia seems to be a slightly more nutritious fodder, but the needle-like hairs on the leaf sheath discourage grazers. Which of the developing aquatic weeds on Volta Lake will be acceptable for grazing will be evident with time, but to

date, so few grazers are present that they are hardly representative. In limited areas where grazing stock become abundant, control of the weeds might be affected. Opoku (1973) found near Kete Krachi that when the local bush areas had been burnt and the remaining patches of grass for grazing had dried up, local cattle would graze in the drawdown area. It was obvious that they preferred Echinochloa pyramidalis to Vossia.

TABLE 15. Percentage Composition on a Dry Weight Basis of Some Common Emergent Aquatic Weeds on the Nile[a]

Species	Ash	Crude Protein	Crude Fat	Fiber
Echinochloa stagnina	10.6	5.8	0.93	35.6
Vossia cuspidata	13.8	6.7	3.40	25.8

[a]Source: Anonymous, 1954.

Control Measures Past and Present

Weed clearance for bilharzia snail control.--Bilharziasis control could be effected by a combination of: (a) environmental sanitation, (b) prevention of human contact with water, (c) clinical treatment, and (d) snail control. One of the major difficulties with the last point, snail control, is the high reproductive potential of the molluscs which enable a few survivors rapidly to repopulate a habitat (Anonymous,

1965). Snail control usually involves environmental, chemical, biological, or chemical means. On Volta Lake environmental control, i.e., drawdown with exposure of inshore habitats, has not been a success. As pointed out previously, Bulinus snails take refuge in deeper water amongst Ceratophyllum. Chemical control (i.e., application of molluscicides) would be an expensive operation and necessarily limited to small areas where application would be of use, e.g., in small pools, lagoons, or streams off the main lake.

Biological control of the snails on Volta Lake has been discussed by Pierce (1971). Of the three snail controls mentioned by him only one seems at all feasible, and that is the puffer fish (Tetraodon sp.) which inhabits Ceratophyllum beds. Since these fish are poisonous if not properly prepared, they are seldom eaten. But they are known to cut fish nets with their sharp teeth and may eat the tails of netted fish; fishermen usually kill them when they are caught. Pierce recommended that fishermen be taught the beneficial role of these fish, so that they would be released unharmed, thereby helping their numbers to increase. But at present no practical technique exists for biological control of Bulinus in this lake.

The most promising technique for reducing snails in specific localities is the mechanical removal of the weed substrate. A pilot program to test this technique has been in progress for some time at Ampem on the western shore of the lake (Pierce, 1971; Pierce and Opoku, 1971). Here in 1969,

a large plot of drawdown area directly in front of a fishing village was cleared of all vegetation, dead logs, bushes, etc. The plot was then scraped clean with heavy farm equipment and sprayed with a mixture of "fenac" and diuron(24 and 0.7 kg/ha). This treatment effectively prevented the growth of aquatic and semi-aquatic weeds when the plot flooded in July. The adjacent control areas developed extensive beds of Polygonum and Ceratophyllum.

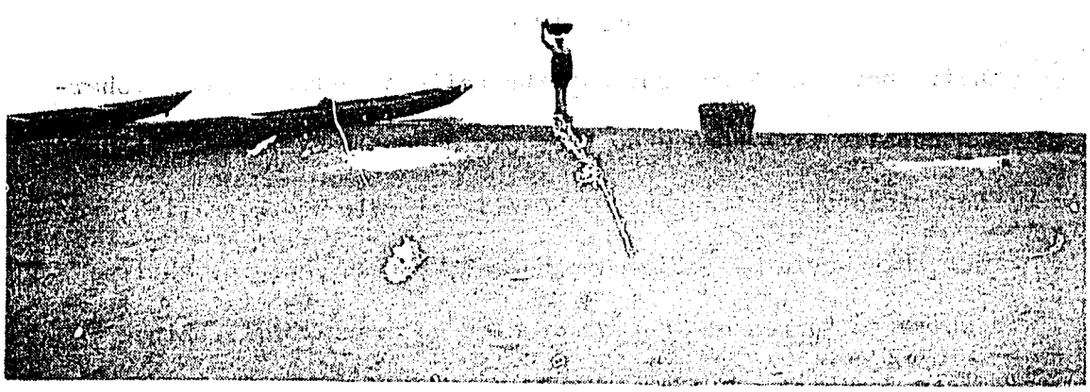

Fig. 6. Ampem shore cleared of weeds (August). Risk of schistosomiasis infestation and navigation obstacles have been reduced by weed clearance here. Dry season growth has been cut in advance of rising lake level to discourage new growth after flooding of the drawdown zone. Schistosomiasis infestation risk is increased by people who enter the lake to draw domestic water. Dug-out canoes typical of river folk are hazardous on the open lake during high winds or storms.

Maintenance was carried out during the flood period (July-November) to ensure that any debris, floating sudd, islands, pieces of Ceratophyllum, etc. would be removed from the test plot. Quite a substantial amount of Polygonum was brought into the area by fishermen who used this plant to cover their catch. When this section of shore was again exposed during the 1970 drawdown period(December, 1969-June, 1970), it was found that there were no weeds. In regard to the effect that this had on local Bulinus snails, Table 16 summarizes the results.

TABLE 16. Bulinus snails found in Ampem study area[a]

Years	4 months before clearing	After Treatment	
		Cleared test plot	Uncleared control
1969	38	1[b]	210
1971/72	---	0	597

[a]Source: Pierce, 1971; Opoku, 1971.

[b]On a piece of Ceratophyllum washed in from outside.

In a program of this type, constant maintenance and continual, accurate snail surveys are essential for its success. "If a single snail is introduced into a favorable habitat it is possible, owing to its exceptional reproductive capacity, to have a flourishing snail colony in about 40 days and transmission of schistosomiasis(bilharziasis) in about 60 days." (McJunkin, 1970).

Clearance of fish channels.--In an attempt to increase access of fishermen to more productive sites, several schemes are being mounted in African lakes. In Lake Chilwa a weed-cutting machine is being used to open areas in the *Typha* swamps which surround the lake (C. Howard-Williams, pers. comm.). In Volta Lake such techniques are not yet applicable because: (a) the inundated vegetation and debris would effectively block such an operation, and (b) Vossia does not form a "bottom-rooting" mass of rhizomes like *Typha* or *Phragmites*. *Vossia* stems would be too difficult to mow during the flood season.

In the Volta Lake, the rank growth of water weeds, especially after 1969, interfered with the laying of gill nets. By that time, it had become evident that *Polygonum* beds were productive fisheries and a number of trials were undertaken to develop techniques for clearing fishing strips in these beds(Pierce, 1971). Clearing of strips in *Vossia* beds was also accomplished.

In *Polygonum* beds the best control was obtained by a combination of cutting and removing the vegetation before flooding, herbicide treatment, and the windrowing of the cut vegetation in the area to become a fishing strip. Herbicides were not found to be absolutely essential, however, for *Polygonum* control. Of the three procedures, the latter was the most effective if cutting and windrowing were initiated immediately after drawdown commenced in December. In other trials it was found that fishing strips could be formed in *Polygonum* beds if cutting commenced at the water's edge as the lake level rose during the flood. The fresh cuttings had to be removed from

the flood zone to prevent them from becoming re-established. It was estimated that to clear one hectare of weeds, approximately 30 man hours were required.

In the Vossia beds more work was required to obtain effective clearing. Before flooding the grass had to be cut, allowed to dry, and then burned. Because burning does not destroy the plant's buried rhizomes, and because the weed is capable of vegetative reproduction in water up to one meter deep, post-flood hand weeding had to be carried out to control new shoots. This proved effective but very laborious. Also, Pierce noted at one place that fishermen had painful encounters with the electric catfish Malapterurus electricus while weeding. Although not considered hazardous, the shock did discourage the fishermen from seriously participating in the program. Additional exposure to schistosomiasis would be another hazard. Pierce doubted that fishermen would expend the energy needed to clear and maintain fishing strips in the Vossia beds, in view of the fewer returns and the availability of other fishing alternatives.

Biological control.--Some of the emergent weeds on Volta Lake are subject to natural biological controls. The burrowing mayfly, Povilla, seriously damages some Polygonum populations. Pierce(1971) also found a small beetle, Atlica, attacking Ludwigia leptocarpa. Attinou (1970) found a snail, Physa, and a moth, Tortrix, which attacked Pistia. The moth lays eggs inside the leaves, and when the larvae hatch out they feed four to seven days on the leaves. Later, the caterpillar stage builds a nest from leaf pieces and continues

to feed at night for three weeks, until it becomes a moth and leaves the plant. He found a two-meter mat of Pistia was destroyed in 14 days by the moth and snail. As yet, no controls have been found for Vossia or Ceratophyllum. And so, although Polygonum and Pistia may be affected, the more aggressive weeds continue to grow unchecked. The manatee, Trichechus spp., is indigenous to the Volta Basin and consumes large quantities of aquatic vegetation. But it is now rare in the lake and is not likely to become a significant factor in water weed control. Fishermen would not tolerate its interference with traps and nets set in weed beds. Also the manatee is highly prized as food.

Environmental control.--In some man-made lakes in the United States, control of aquatic weeds is obtained by drawdown. Thus, Richardson (1973) reported 50-95 percent control in shallow ponds, lakes, and reservoirs in Louisiana by drawing down until a 40-70 percent reduction in surface area is achieved. This type of drawdown is not possible on Volta Lake. Although the lake's surface is reduced by approximately 40 percent during drawdown to the 250-foot elevation, the drawdown is so gradual that the weeds adjust their growth to new water levels or survive exposure on moist drawdown soil.

Cost of Control

Chemical control.--Pierce (1971) carried out herbicide trials using a number of compounds commercially available in Ghana. A summary of his results is presented below.

a) Scirpus sudd:

Paraquat (1.25-3.75 lbs AE/ha)--very effective but quite expensive at $75/ha.

2, 4-D amide, granular--also effective, the granules lodged in the sudd and then dissolved. Too expensive for ordinary use ($100/ha), but would be useful from a helicopter during a weed epidemic.

Diuron (Karmax, 80 percent wet powd.)--used as a direct spray, it was quite effective and cheaper than most ($12/ha).

b) Emergent weeds on drawdown area:

2, 4-D ester--quite effective against seedlings and young plants, but of no use on older Ludwigia, Polygonum, or Alternanthera. Cost $8/ha.

2, 4-D amide--same as above, but not quite as effective. Cost $6/ha.

Paraquat--as good as 2, 4-D ester, but more expensive at $15/ha.

Diuron (Karmax, 80 percent wet powd.)--if a fast kill is desired this would not be satisfactory, but for slower kill it is quite effective. Cost $12/ha.

c) Emergent grasses when stranded on exposed soil:

Dalapon--controlled Vossia, Echinochloa, Andropogon and Paspalum at $34/ha.

d) Ceratophyllum:

Paraquat--did not work because of silt in the water (which inactivates it); possibly it would do a better job in clear water, but very expensive at $200/ha.

Fenac (24 kg AE/ha)--if the exposed mud is sprayed before flooding, Fenac will kill all weeds (especially Ceratophyllum) and weed seeds for some time after floods, but it does have one side effect in that it inhibits crop growth on soil during drawdown. This would be a problem except where land is still available. Another serious drawback is the cost for such soil treatment: $400/ha.

Mechanical control of weeds at Ampem.--Costs are derived from the pilot project at Ampem which initially focused on a three-hectare plot in front of a fishing village (Pierce, 1971). Herbicides were used in initial clearing in 1969, but were applied only to a 1.5-ha section in 1970. Clearing was expanded in 1971 increasing the previous shoreline.

The prevention of a re-colonization of cleared areas requires good timing and considerable labor. Workers must be engaged before the rains so that before the flood begins all hand-cutting can be done. The first task is clearing the weeds from the drawdown area, then burning and cutting. The job becomes difficult as the rains increase. As the waters rise, debris floats in which must be cleared. After flooding, some men must remain to clean up debris on a part-time basis. After this, the area is left until the following year.

a) Equipment needed for initial weed clearance:

(Note: Usually this equipment is available during construction of a dam and/or resettlement housing. If not, the cost of renting or buying must be included in the initial cost.)

Chain saws
Steel towing cables
Axes and cutlasses
Farm tractor
Cultivator and blade*
Trailer, flat bed
Lorry
Spray pump and spray gun

---

*Road grader might have been much more useful (Opoku, pers. comm.).

b) Initial weed clearance in April, 1969:

Physical labor (weeding, stumping, burning, carting) 81 man-days @ $0.75/day	$ 61.
Mechanical operation (chain saw, tractor, cultivator) 28 man-days @ $0.75/day	21.
Spraying, 12 man-days @ $0.75/day	9.
Fuel (gasoline, diesel, oil).	75.
Spray--300 Fenac @ $3/1 (covered 1.5 ha only)	800.
Spray--14 kg Karmax @ $3/kg (covered 1.5 ha only)	42.
Initial Cost Total	$1008.

c) Maintenance cost, 1970:

No cost. The original area was cleared by self-help project. This approach was not feasible in the following year when the project was expanded.

d) Cost of plot maintenance and expansion, 1971:

Physical labor, 732 man-days @ $0.75/day . .	$ 549.
Mechanical operation, 18 man-days @ $0.75/day	14.
Fuel	24.
	$ 587.

Since the cleared area of drawdown was to be increased to include 30 additional hectares (1.2 km of shoreline) some variations were attempted during 1971 to find an easier way of clearing. In June 1971, the area was mowed three times using a rotary mower on a farm tractor.

Ceratophyllum was also removed from offshore by raking. As the water rose there was a lush growth of weed in the "pre-soak" zone (i.e., the Seedling Zone), and this could not be easily cut or burned. It was decided to hoe these weeds out to prevent regrowth from seedlings or stubble. Ten men were hired to do the job, each being assigned a given area to hoe, rake, and burn each day. The water was rising rapidly, and ten more men were assigned to cut up logs which floated in with debris and to keep the beach clean.

e) Maintenance costs on expanded plot, 1972:

Approximately 15 men were used for clearing, but costs remained approximately same as for 1971	$ 590.

f) Summary:

Total cost of project for 4 years.	$2185.
Average yearly cost (with initial spraying). .	537.
Average yearly cost (without initial spraying).	333.
Estimated cost per hectare (33 ha, without spray)	10.

Possible Directions for Future Weed Control Programs

Weed control.--At Volta Lake the most pressing weed problem is the growth of *Ceratophyllum*, which serves as a substrate for *Bulinus* snails. The second most important weed problem is the growth of emergent weeds which interfere with inshore fishing and transport. Weed clearance for snail

control is often suggested as a cure-all, when in fact it is only a stop-gap measure. The ultimate control of bilharziasis is a public health problem, with many aspects involved such as sanitation, clinical treatment, etc. No matter how clean a shoreline is, infection and reinfection are always possible from snails in protected areas such as pools, lagoons, and streams, outside the lake, or in deep water areas in the lake itself. The only weed clearance technique on Volta Lake which has worked well involves burning, cutting and hoeing. Such clearance, if done rigorously and timed to occur just prior to the flooding, is cheaper and safer than herbicides. The self-help manual weeding campaigns have not been successful (Opoku, 1971), and this poses the problem of future support for such programs. Also, although manual clearing is useful for snail control and opening channels for fishing and transport, it has little or no effect on Ceratophyllum. Although hand-clearing of this weed has been attempted at Ampem, where a boat and three workers have been operating on a part-time basis for some time, the weed is still present in quantity.

Few alternatives exist for control of Ceratophyllum. Possibly the weed-eating fish species of Volta Lake may provide some control, and this should be investigated. Most effective herbicides are too expensive to use on anything other than small plots, but the use of new chemicals such as glyphosphate (which may be ecologically safer than most herbicides) in combination with herbicides may result in a more effective and

cheaper control (Riemer and Welker, 1973). Hand-weeding (with rakes) along with chemical control might also be cheaper than chemical control alone. All of these methods should be examined in field trials. Furthermore, new weeds such as Potamogeton and Vallisneria should be included in future trials. The use of any new chemical or herbicide should of course be preceded by laboratory and field toxicity tests on all potentially susceptible organisms, in addition to control effectiveness tests on target plants. Adverse effects must be carefully assessed before any decision for widespread use.

Weed surveys.--Pierce (1971) recommended that at least one aerial survey of the lake be done each year, in order to spot weed development in isolated areas. This apparently has not been possible for the last few years, but at the least, spot-checks should be carried out routinely by boat. These spot-checks should include sites within all of the major branches of the lake. At present, the major sudd areas are located in shallow bays, especially in the arms of the lake where rivers enter. These areas should be watched to determine if the sudd areas change with time. Observations during and after flood periods would be particularly important.

Weed biology.--Although some of the aquatic weeds on Volta Lake have been well studied (e.g., Pistia), there are still several weeds which must be studied more thoroughly. The weed biology of Vossia and Ceratophyllum, especially their life cycle, reproductive potential, growth, nutrient relationships,

substrate preference, etc., must be known before any real headway can be made against their control in Volta Lake. One additional subject that merits research concerns the function of weeds such as Vossia in providing food and possibly shelter to young fish. Unless more is known about what part aquatic weeds play in the Volta Lake ecosystem, weed control projects cannot be properly planned with minimum disturbance to the environment.

7. Fish Nutrition and Production

Introduction

The objectives of this survey were to investigate the present status of fish production and nutrition in the Volta Lake, and to attempt predictions of the possible future condition. A further objective was to make a preliminary assessment of the possibility of increasing productivity through artificial fertilization.

Owing to the limited time available, the work was necessarily limited in scope and superficial in some details. In lieu of extensive field surveys, most of the data were collected from recent reports and publications, and from extensive talks with many hydrobiological and fisheries workers on the lake.

Several short field trips were made on the Volta Lake to gather firsthand information about biological productivity in different lake regions (see Appendix II). The information was chiefly pieced together in the Volta Lake Research Project laboratories in Akosombo and the Volta River Authority library in Accra.

This section presents introductory remarks on the Volta Lake which lead to data on fish production and nutrition, a detailed assessment of the present knowledge of stocks and feeding patterns of the more important Volta fishes, and recommendations.

Primary Production and Fish Nutrition

The chief primary producer in the lake, in terms of availability to fish and invertebrate consumers, is the carpet of periphytonic (aufwuchs) and benthic algae, chiefly diatoms. In many cases the same species occur in the water column, leading to ambiguity in stomach analysis conclusions. Substrates available to periphyton are very considerable owing to the abundance of flooded trees and vegetation. However, quantitative estimates of substrate surface are not available for the Volta Lake (Bretschko, 1972).

Rooted aquatic vegetation is patchy, occurring inshore only in the more sheltered areas. However, a feature of growing importance is the annually flooded shore sward in the drawdown area. During the dry season this is either cultivated or colonized by sedges, *Polygonum*, semi-aquatic grasses such as *Vossia*, and legumes, with a fringe of savannah (Andropogoneae) grasses along the top (Hall, 1970). Some, notably *Polygonum* and *Vossia*, can float with the rising waters, and others can tolerate prolonged submergence. Unlike *Pistia* (now restricted to sheltered bays where inflowing water brings enough nutrients (Hall and Okali, pers. comm.), these do not shade the surface so as to cause oxygen deficiency beneath, but they may constitute an important fish nursery and refugium. Many invertebrates abundant on drowned trees are now colonizing this vegetation, and flooded leaves are often eaten by fish. It is clear that drawdown vegetation is an increasingly important source of

nutrients for the lake, and its annual biomass (approximately equal to production) is estimated at about 6-13 g m^2 day^{-1} (Hall, 1970), which is relatively high.

Nutrition Studies

Volta fish diets were studied by Petr (1967a,b, 1968), Reynolds (1967, 1968, 1970), Whitehead (1969), Loiselle (1970), Vanderpuye and Ocansey (1972), and Adiase (1969). The original river fauna was dominated by insectivorous surface-feeding fishes such as Alestes and Eutropius, in many cases potamodromous, and capable of exploiting the rich, yearly drowned floodplains. The emphasis has rapidly swung, in the more lacustrine areas, to a predominance of benthic and algal feeders in the families Cichlidae and Bagridae, the former comprising the major part of the fishery. Piscivores such as Lates offshore and Hemichromis inshore have apparently increased and also breed in the lake. Many of the commonest species appear to be facultative rather than obligatory feeders on a particular foodstuff.

Few fish exploit the scanty and patchy zooplankton alone, but a diet of zooplankton supplemented by emergent aquatic insects supported the rapid development of large stocks of pelagic clupeids (Pellonula), considered to form the largest biomass in the Volta Lake (Vanderpuye, 1972).

A description of fish nutrition by species is best organized by treating species of the southern and northern portions of the lake separately. In the southern lake environment the

riverine insectivores have been replaced by Tilapia species--highly adaptable, primary consumers with a range of food specializations. Stomach analyses (Petr, 1968; Reynolds, 1968, 1969; Whitehead, 1969; Ocansey, pers. comm.) together with Scuba diving observations for some species (Kramer, pers. comm.) indicate that T. galilaea eats chiefly phytoplankton, and T. nilotica adds to this diet higher plants and bottom deposits with periphyton, which they collect inshore in flooded savannah and bush. The less abundant T. zillii prefers dead plant material, but the species also takes terrestrial and aquatic insects and algae (Petr, 1967b). Correspondingly, T. galilaea is generally caught offshore in gill-nets, T. nilotica inshore in traps.

A second major fish group in the southern lake is the Chrysichthys species group, very abundant inshore. These are apparently well adapted to a sandy-silty substrate, where they feed on benthic algae and invertebrates. Their rise in abundance has been slower, but more sustained than that of Tilapia. Small Chrysichthys are caught in beach seines or cast nets and used as long-line bait for the major predator, Lates, and most recent information and personal observations suggest a decline in gill-netting for Tilapia, but an increase in open water long-lining for Lates.

The Lates themselves are chiefly feeding upon a third major stock of fishes in the lake, the pelagic clupeids Pellonula.

This species dominated stock assessment catches in 1969-1971 (Vanderpuye, 1971) and held this position despite a decrease in absolute fish abundance over this period. Lates probably also feeds inshore (Loiselle, 1971) possibly following the migrating clupeids, and also taking small Tilapia and Chrysichthys (Vanderpuye and Ocansey, 1972).

From all this we can draw a simple food-web based chiefly on attached algae on the bottom and on submerged trees. As the southern lake matures, the terrestrial component of the diet is expected to become less significant. An important exception to this is in terms of drowned plants and associated fauna which may become seasonally available on the wider drawdown areas; this is discussed further below.

The dominant inshore fishes at present (Tilapia and Chrysichthys) feed on these algae and their associated fauna, while offshore, Pellonula feeds on plankton and emergent insects from submerged trees. Tilapia is a minor component of the diet of Lates, but Pellonula is a major component. Pellonula and the other insectivorous forms depend chiefly on the large and prolific mayfly Povilla adusta, which burrows in drowned softwood trees such as Ceiba pentandra (silk-cotton); other invertebrates are few and small (chironomids, trichopteran larvae, oligochaetes). The activities of Povilla have rapidly eroded the remaining softwoods, adding to the above-water attacks of dermapterans and boring beetles, so

these trees may soon be gone from the lake. Hardwood savannah trees (Cassia, etc.) form the majority of those flooded. These bear aufwuchs algae on their corrugated surfaces, but do not offer as suitable a substrate for Povilla (Petr, 1972), the surfaces being colonized by the smaller chironomid larvae and trichopteran larvae. As the latter are likely to be partly carnivorous, this puts a further step into the food web, the effect being to remove the Lates further from the primary energy source (algae), with a consequent diminution in energy available to it. Thus we can expect Povilla to decline and its place in the food web to be occupied by smaller forms, with a consequent decline in the fish populations dependent on it--chiefly the clupeids (see Figs. 7, 8).

In the northern lake, however, the situation is somewhat different, representing perpetuation of a transitional stage in the development of the lake forms. Mormyrids have largely retreated to the rivers themselves (Petr, 1967), but this may not be as complete as was once thought (Kramer, pers. comm.). Flooded trees are the basis for spatial organization of a characteristic fish assemblage including Synodontis, Leptotilapia, Petrocephalus, Labeo, Bagrus, and Malapterurus. Aufwuchs is apparently very important to these as food. The pelagic zone is sharply defined over the original channel by the submerged fringing gallery forest; in it are schools of Eutropius, Alestes barmose, A. dentex, Cynothrissa and

A. leuciscus; their abundance depending on their seasonal potamodromous migrations. These eat mainly surface insects and emergent aquatic forms, supplementing this diet with small fish. Fishing methods in the northern lake are similarly sharply defined, specializing in the capture of either pelagic or inshore fishes.

The story as outlined above can be modified in several ways. The drawdown area reaches its greatest extent and is least disturbed by man on the flat western shores. In the east, shores are steeper and cultivation more intense, while in the north the drawdown is in places farmed and grazed by livestock (Hall et al., 1971). The drawdown floral community is still evidently in transitional stages of development. Indications are that floating and light-excluding mats of Scirpus and Pistia sudd are now confined to a few southern bayheads, owing largely to their nutrient demand and vulnerability to wave exposure (Hall, pers. comm.). But the greater part of the drawdown is becoming colonized by large semi-aquatic grasses such as Echinochloa and Vossia, some of which are attractive to livestock, and by dense Polygonum stands, which, though inedible to cattle, have stout hollow stems attractive to Povilla when submerged. Thus the drawdown vegetation and its removal by cropping will be a significant, perhap deciding factor, in lake fertility. When seasonally flooded, most sedges will die and provide a food source, while

many grasses and Polygonum may grow to keep pace with the rising waters, tolerate prolonged submergence, or float. Such areas are significant to fish as nursery shelters and food sources, and as substrates for attached algae, thus directly providing dead and living plant tissue as well as substrate for invertebrates.

Little mention so far has been made of the benthic invertebrates, usually a dominant food source in lakes. The soils underlying the Voltaian basin are in general light and sandy. A build-up of organic ooze with its consequent rich bacterial flora, such as commonly supports dense populations of grazing invertebrates in temperate climates, is unlikely to occur under these conditions, given the high temperature, good oxygenation of inshore areas, and wind exposure. Benthic populations have remained low (Petr, 1968) and the likelihood of a future increase is controversial. The expected early decrease in flooded softwoods and the slow decline in savannah hardwoods, resulting in reduction in substrate for benthic invertebrates, may be compensated for by the development of a periodically flooded typical drawdown flora.

Pellonula Trophic Web

Many organisms can be assigned roughly to a trophic level, as primary consumers, secondary consumers (predators), etc. Each higher level results in about a ten-fold drop in

stored energy. However, in nature rigid feeding roles are relatively rare in a changeable environment, and in a tropical impoundment where among river fishes only the more opportunist in feeding, behavior, and reproduction can flourish, roles are even less distinct. Thus, we find the lake sardine Pellonula eats Volvox, crustacean zooplankters and chaoborid insect larvae as well as small fish, leading to the following complicated food web. On balance Pellonula is placed at the tertiary level.

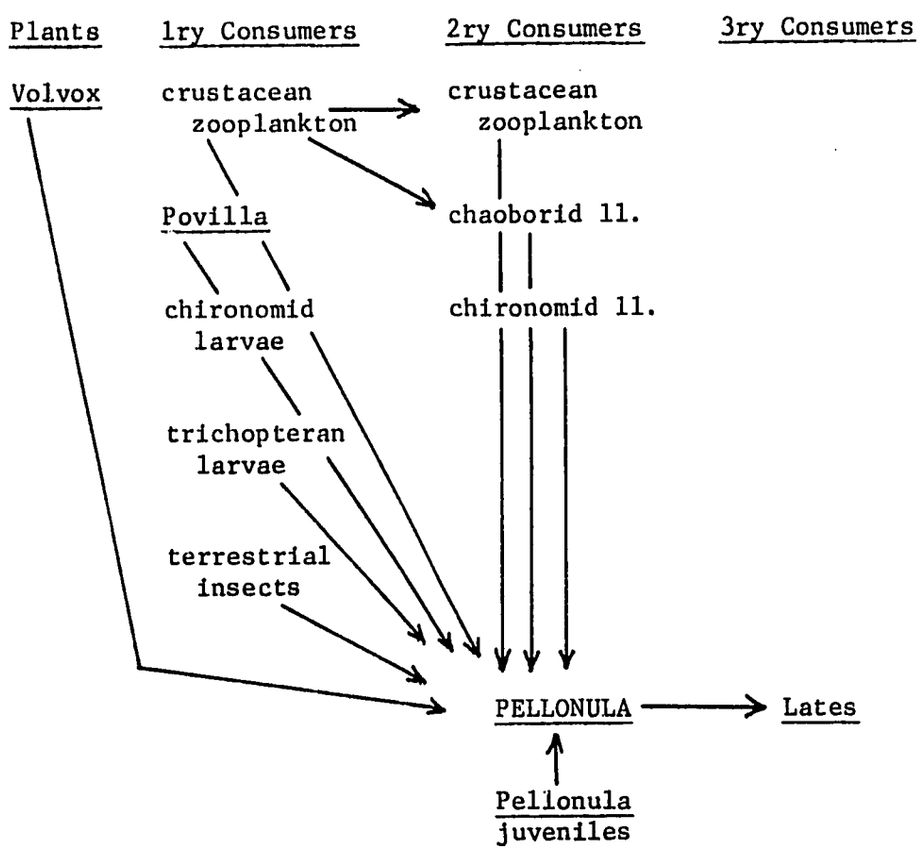

Figure 7.—Pellonula food web.

Fish Production

Information on fish production in the lake derives from experimental fishing with nets or chemicals, and from estimates of fish catch. However, at present there are no total indicators of fish production for the entire lake.

The level of fish production was unknown in the Volta River before the dam was closed, but it has been estimated that in the mid-1950's about 1,000 permanent fishermen (augmented several-fold in the floods) were active, catching perhaps 200 t per annum for the area now flooded (Volta River Project Commission, 1956; Hilton, 1961). Upstream from the lake there is an annual catch of about 2,000 t per year (Welcomme, 1972). Before impoundment, the Volta River Commission (1956) estimated 18,000 t sustainable yield per annum for the reservoir, but this was not considered further.

In the early days of impoundment, estimates of fish catch were made by sampling catches for two to three days per month at seven stations. That these did not cover all habitat types is evident from chance observations, i.e., the differences between two adjacent landings at Yeji--one with benthic and inshore fishes dominated by bagrids, Labeo and Tilapia, the other landing pelagic clupeids, alestids and schilbeids. A feature noticed, but not quantitatively assessed, was the large catches of citharinids seen in the northern arm between Kete Krachi and Yeji before the waters had reached their height; these catches declined after 1966.

Fishing effort steadily built up during formation of the lake, and an estimated population of 60,000 now depends upon fishing for a living. The quantity of catch in more recent years has paralleled the general downward trend in primary productivity. Whole lake catches declined from 61,780 t in 1969 to 39,900 t and about 37,000 t in 1970 and 1971, with indications of a further decrease in 1972 (Agadzi, pers. comm.). The changes of the first two years are directly correlated with changes in total alkalinity (Ryder and Loiselle, in Regier, 1971), and this must also be influenced by the reduced floods over the entire period.

The effect of the reduced floods is two-fold; productivity drops and low waters have high transparency, so multifilament net catches are lower. A strong flood should increase catches both for that and the following year, by improving productivity and by increasing shelter in murky waters and flooded vegetation. It would be valuable if a relationship could be established empirically, and with accuracy, between catch and a measure of nutrients. Loiselle (1970) indicates that the littoral fish production is similar in both north and south lake areas, suggesting that the major differences between them lie in an additional factor--the differing proportion of littoral influence in each.

Estimates for gill-net catches indicate that, for a "constant fishing effort," catches of both Lates and Tilapia

were halved in 1970 compared with 1969, and other species except Alestes were also reduced (Bazigos, 1971). Thus, periphyton feeders, plant eaters and predators all fell off considerably, whereas opportunist surface insectivores did not. This may reflect the effects of decreased floods, which would not affect surface insect life as much as plankton and drawdown zone flora and fauna. At this stage pressure on Tilapia was heavy, but Lates was still only the third or fourth in weight caught. Hilton (1961) reported that mean size of Lates taken at Yeji before impoundment was 30 kg, much higher than the mean weight today. The catch results could be due to the sustained high, inshore fishing effort with gill nets, which take smaller, younger fishes. Size of Lates fished will increase, however, with the shift to hook and line. Until more is known of the ages of Lates in Volta, the effects of fishing effort remain in speculation.

Production studies were first started with estimates of relative abundance of species as indicated by catch in experimental fishing gear (Denyoh, 1969), and calculations of the ratios of different species in the commercial catch (i.e., Petr, 1967). But good assessments of either total catches or total stocks could not be made, owing largely to ignorance of the many small fishing centers catching the bulk of fish.

A statistically designed, experimental fishing program, carried out since 1969, has allowed VLRP to estimate the whole lake catch and relative fish production. The catch at

present is assumed to be stabilizing at the 1970 level of about 37,000 to 39,000 t (Bazigos, 1971), but the sharp drop in fish catches from 1969 to 1970 throws doubt on the representativeness of the 1970 catch level.

Determination of the Lake's Productivity

In general, it appears that fish biomass of the lake had peaked by 1969, although individual groups such as citharinids and alestids had reached peak levels and declined much earlier (Petr, 1967; Reynolds, 1973a).

Ryder's (1965) index of productivity has been applied to the Volta Lake (Vanderpuye, pers. comm.) and gives a first approximation of the lake's potential. This is a morpho-edaphic index expressed as the total of dissolved solids in mg/l divided by mean lake depth in meters. For the Volta Lake the value is 3.7, which suggests 35-40 kg/ha of production, or about 40,000 mt per year of sustainable yield. This is close to future yield predictions made by Ryder and Loiselle (Regier, 1971), and is close to the annual average yield of 45 kg/ha (Agadzi, pers. comm.). If the computation based upon Ryder's index is accurate, it indicates that the lake's yield is now close to its entire production, and small increases in fishing intensity could deplete the stocks now present. However, as mentioned above, the bulk of the lake's biomass is thought to be comprised of the pelagic *Pellonula* spp. which are not

fished commercially, hence the relationship between total calculated productivity expressed as biomass and estimated fish harvest is not direct. As Vanderpuye (1972) pointed out, many species are lightly fished while others are taking the brunt of the effort. A second qualification is that Ryder's index does not take into account how production may be apportioned between benthic algae and weeds, or between herbivorous or carnivorous invertebrates and fishes. In extreme cases, there could be an order of magnitude between high and low estimates.

Loiselle (1970) estimated littoral ichthyomass to average about 120 kg/ha using rotenone. Since the littoral serves as a nursery area and is probably the main food source of most species, this figure may be greater than the open-water biomass, where the chief fishes are the abundant clupeids, Alestes baremose and A. dentex, and the schilbeids. No present method of assessing their absolute abundance or production is feasible, although relative figures are available from experimental fishing.

Ryder's index was applied to Lake Kainji, and gave a value range of 3.2 to 4.5. Kainji has a more limited littoral and is more intensively fished than Volta. The resulting productivity calculation of at least 4,100 mt per year was comparable to the lower range of productivity calculations made by Henderson (Ita, 1972) using different methods. Henderson assessed fish productivity in Kainji by assuming an average

food-chain length of 2.0 and estimating primary productivity at 3.6 g C/m^2/day. From this he derived potential fish yield estimates for Lake Kainji of 35-150 kg/ha, or around 4,000 to 16,000 t per annum. Other sources look for a sustained yield of perhaps 10,000 t per annum.

While these methods of calculating productivity give rough approximations, more accurate information is required for the purposes of predicting future yields of fish. It seems, however, that productivity as indicated by biomass estimates, cannot at present be directly measured. Mark-recapture methods to obtain absolute data on stocks were early considered, but judged impracticable in terms of fishermen response and the scattered villages. However, now that most settlements are served by transport launches and many are familiar with the catch-recording teams, such a program might be implemented with adequate support. Many of the original objections were based on unfortunate experiments in East Africa, where tags were more prized as adornment than for their reward value; this is unlikely among the more sophisticated fishing groups on the Volta. A returned tag with a measure of the fish's total length could give much information on migration patterns, growth rates, and indeed stock size. The scheme should concentrate initially on a commercially valuable and relatively hardy species such as Lates. Further evidence on productivity could be calculated if large unbiased

samples of population were collected, i.e., by rotenone plus netting, to determine age-dependent mortality. The growing long-line fishery could also provide a fairly unbiased sample. This would need to be correlated with estimates of species fecundity, but to combine such data realistically is difficult.

Future Fish Productivity of the Volta Lake

The Volta Lake has been variously subdivided for different biological assessments; i.e., for catch statistics into seven major "strata," discussed by Bazigos (1971) in terms of four main biological areas, the Afram Arm, Lacustrine Zone, Interface (below Kete Krechi) and Northern Arm. Czernin-Chudenitz (FAO, 1971) considers the lake to have three main regions, the main lake, riverine arm, and tributary bays, although he admits that the last is a mixture of the first two in character. Petr (pers. comm.) considers the productive, relatively shallow Afram Arm as worthy of separate consideration. The main lake, and Bazigos' first three regions, correspond to the "southern lake" zone of Reynolds (1970).

For most planning purposes the lake could perhaps best be considered as two major sections: north and south. The transition between these is gradual and many miles wide, and its position moves north and south with the changing seasons. The northern arms are narrow, shallow, and dominated by extensive areas of flooded savannah bush; there is appreciable water

movement and high turbidity at the floods, and the principal fish stocks are potamodromous, surface-feeding alestids, schilbeids and cyprinids. Species diversity is high, and inshore benthic fisheries take substantial numbers of mochocids. In its strongly riverine quality, the region resembles the Niger central delta or the major part of Kainji reservoir, although there, drowned trees are less prevalent (Regier, 1971).

By contrast the southern lake is lacustrine and has essentially completed its evolution--future modifications will come through changes in the drawdown vegetation and cultivation patterns, and the gradual disappearance of flooded trees. This is the area generally thought of as the "Volta Lake". It is open and scenic, and owing to its proximity to Akosombo, has been most thoroughly studied. It seems evident that here phytoplankton numbers peaked in 1968, as did alkalinity and $CaCO_3$ levels; pH was also highest (7.0) then, but has since declined to between 6.6 and 6.7 with the decreasing buffering power (Biswas, pers. comm.).

Apparent trends in trophic chains in the lake provide one indication of the future productivity of the lake's fisheries, although the projection of such trends is admittedly speculative. Figure 8 illustrates simplified food webs for the Volta River and the lake in early stages, and subsequent evolution to the present quasi-stable situation in the northern region, and in the southern lake to a "stable-declining" pattern.

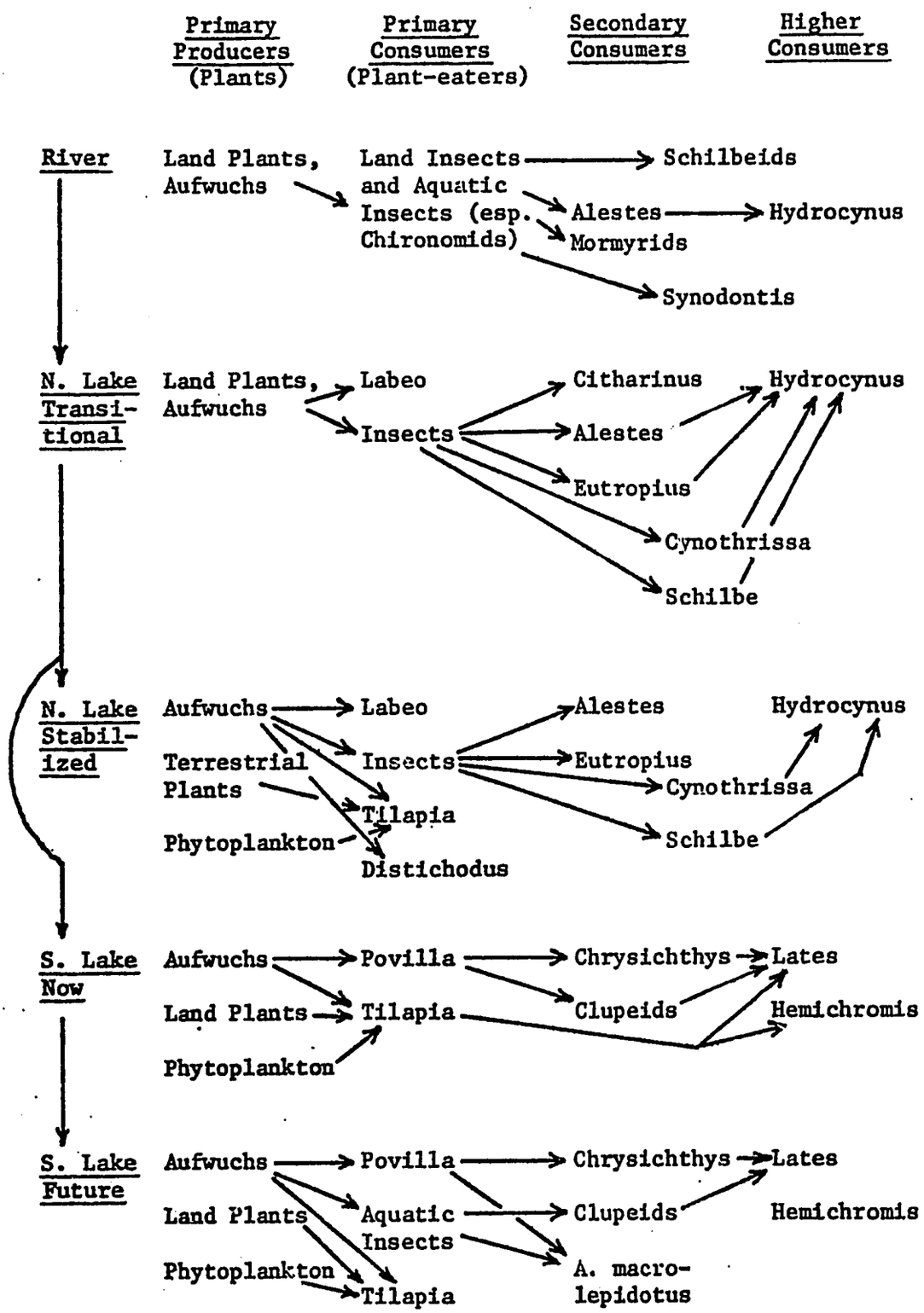

Figure 8.—Lake developmental sequence: simplified typical food chains, Volta Lake.

Future patterns are likely to show a continuation of the increase, both north and south, in primary consumers (Labeo, Distichodus, Tilapia) and in the inshore dominance of bagrids (Chrysichthys species) in the south. In the open water fauna in the south, more emphatic domination by Pellonula and its predator, Lates, can be expected. The latter is far removed from the primary food source, and can never be expected to reach enormous overall levels. Indeed, Okorie has suggested (1972) the elimination of Hydrocynus and Lates in some African waters to increase catch of "food fish."

At present Lates ranks second by weight after Tilapia in the commercial catches, from perhaps third in 1970 (Bazigos, 1971), and second to Pellonula in experimental catches (Vanderpuye, 1972). There are several possible explanations. Catch data suggest Lates is either being underfished or that pressure on other stocks is too light, but the experimental fishing data suggest perhaps that populations of Lates may be unrealistically high for a fish predator, and might warrant increased fishing. Vanderpuye (1972) found that until 1969 Lates formed only 11 percent of commercial catch but 38.5 percent of experimental fishing. Their abundance might have followed the build-up in Pellonula, and they may have been responsible for the decline in abundance of that species since 1969. Condition in Lates has also declined since 1969 (Vanderpuye and Ocansey, 1972) as have numbers caught; this points to a decline in available food.

An increase in Lates catch could also indicate overfishing, however. Many of the criteria used as indicators of overfishing (Evans, 1969), e.g., decreased catch per effort, reduced yield of larger fish but increased number of smaller fishes in catches, decreased catch of species under heavy exploitation, may not be applicable to Lates. The present fishery methods catch immature fish as well as adults. It therefore would seem important to get a reasonable estimate of stock size of Lates in the lake. A mark-recapture program could accomplish this, but would have to be continuous owing to small catches probably available. Even if concentrated on the south of the lake, it would give some indications of stock.

The experimental catch data indicate a decline in all Lates age classes equally, which has been interpreted as indicating a change in lake productivity. However, declining productivity probably would first be felt in lowered fecundity and reduced numbers of juveniles, as these are most vulnerable to food shortages; thus the size distribution would be skewed in favor of the adults.

Important fish stocks which may be increasing in the lake, or at least holding their own, include Labeo species, now third in catches (Kramer, pers. comm.), Alestes macrolepidotus (Reynolds, 1973a), at present minimal in fisheries according to Loiselle (1971), and Chrysichthys species. These are, respectively, mud and aufwuchs feeders, surface and opportunist feeders, and benthic insect feeders, and they cover

a wide spectrum of feeding types. A slow sorting out of the most suitable species for lake niches is bound to occur, and these groups may eventually displace species important at present. Again, studies of changes in diet of a species as the lake has matured (i.e., Reynolds, 1973a) could be helpful to our understanding of the stabilizing of such impoundments.

The apparent general decline of Lates stocks probably reflects the general diminution in fish abundance in the southern lake, but this also needs further study. There seems to be a natural regulation of fishing effort, for as the stocks decline nets become unprofitable and fishermen either migrate away or change to farming for at least part of the year, thus taking the pressure off the stocks. The notion of a widespread refugium for fishes among trees and weeds (Evans, 1969) is not very convincing in the southern lake, but it may be more important in northern areas.

Suggestions have been made for the provision of artificial substrates or refugia in intensively fished areas. Floating open water devices might also be experimented with in midlake to attract fish (i.e., Hunter and Mitchell, 1968; Klima and Wickham, 1971). Gear for rational exploitation of stocks might concentrate rather on moving surface-midwater trawls for open waters, where 70% of the biomass is concentrated in the clupeids, rather than large-mesh gill-nets inshore. Large beach seines seem unsatisfactory, and Vanderpuye (1972) suggests their discouragement, as they can destroy cichlid nursery areas.

Lake Fertilization to Enhance Fish Production

An assessment of the possibility of increasing Volta Lake's productivity by fertilization of the waters must consider other sources of nutrient input to the lake waters which might have the same purpose. This would indicate the possible level of nutrients necessary. A second consideration is the possible side effects that sudden, large-scale nutrient addition might cause.

Uncontrollable sources of nutrient enrichment to the lake include drainage from fertilized adjoining land and from natural land areas, sewage and offal from lakeside settlements, and natural flood season enrichment from river waters, drowned shores and hypolimnion mixing. Hypolimnion accumulation of phosphates and ammonia, when these are limited or exhausted in surface waters, represents a kind of nutrient holding bank rather than an additional source. River inflow is known to vary considerably from year to year; the years 1970-1973 were below average floods, resulting in decreasing lake levels and lessened nutrient input. The productivity of the lake may therefore be expected to have perturbations introduced at irregular intervals by fluctuations in river flow. This circumstance weakens the predictive value of lake productivity measurements.

The nutrient-providing effect of the drawdown is likely to be most heavily influenced by increased cultivation

and fertilization. Fertilizer residues in the soil would add to lake productivity at high water. Also, if the drawdown vegetation of perennial, flood-tolerant grasses and Polygonum is used, either cut for mulch or as fish-shelter cum productivity-enhancer in the shallows, the nutrients locked up in it would be more fully released. Vossia, although a haven for fish, is not a source of major fish recruitment, and there have been suggestions that it should be burnt at the end of the dry season to release nutrients and to provide aufwuchs substrates (Volta Lake Research Project, 1971).

Fertilization of the lake itself would be a major undertaking. In about four years the lake water can theoretically be replaced. Fertilization must then be regularly repeated to be effective, whereas in a natural lake with a small outflow-to-volume ratio, the nutrient input which is present can be locked up temporarily or permanently in the sediments, and have a more prolonged effect on trophic level.

No fertilization experiments on anything like the scale of the Volta Lake have been attempted in the past. The largest trial was done by Parsons and colleagues (Parsons et al., 1972; LeBrasseur and Kennedy, 1972; Barraclough and Robinson, 1972) on a large, deep oligotrophic lake in British Columbia. They found that weekly addition of liquid fertilizer resulted in enhancement of algal production (though not of biomass), a ten-fold increase in zooplankton, and about a 30 percent increase

in growth of zooplankton-eating fish. Many small temperate lakes and ponds have also been fertilized to enhance productivity (i.e., Nelson and Edmondson, 1955; Hall et al., 1970).

Tropical conditions are much different; experiments in these regions have been restricted to fish pond culture experiments using traditional natural fertilizers (sewage, fresh vegetation and offal) for extremely high yields, and commercial fertilizers. The first have been adequately reviewed in many papers. In Bouaké, Ivory Coast, where the savannah conditions resemble those around much of the Volta Lake, the Centre de Pisciculture under Lessent has been adding fertilizer to 400 m^2 ponds. Here liming at 500 kg/ha every two to three months to maintain a pH around 7.0 was followed by sulphate of ammonia addition, with or without superphosphate; these nearly doubled production of Tilapia species and Heterotis (both phytoplankton feeders). However, fertilized but non-limed ponds also showed comparable increases in production (Lessent, 1966, 1967).

It is probable that a similar increase in yield could be obtained if small arms of the Volta Lake were ponded off and fertilized; these areas are generally relatively low in fertility (Loiselle, 1972) and, indeed Ghana soils are generally nitrogen-deficient (Volta River Project Commission, 1956). However, such a process should be examined separately and the whole question of shoreline rice paddies with fish culture in them should be considered in detail, along with the consequent

danger of increasing insect vectors (principally mosquitoes) and Bulinus snails, as a separate problem. For a guide to fish culture in ponds, the great mass of experimental and practical knowledge from Southeast Asia can be used.

At fertilization rates used in Bouaké ponds, the Volta's 8000-km^2 surface would require about 300,000 t and 465,000 t of superphosphate and ammonium sulfate, respectively, over a 12-month period to achieve perhaps a 50 to 75 percent increase in fish production, all other factors being equal. However, stocking, harvesting, water levels, distribution of fertilizers are all controllable in ponds, but are unknowns in large lakes.

The estimates derived from the Bouaké are almost certainly too high. Alternatively, using the data from Parsons et al. for a lake 1/160th of Volta's surface area, and about 1/16th the volume, the 12-month comparable rate for Volta would be over 42,000 t fertilizer added on a surface area basis, or about 4090 t calculated on a volume basis. These calculations are also quite unrealistic as Volta differs quite as much from Great Central Lake, B.C., as it does from the Bouaké fishponds. Differences lie not only in climate, mean depth and aquatic life, but also in outflow-to-volume ratio, which in Great Central Lake is only about 1/400th that of the Volta.

Fertilization of the Volta Lake as a whole at this time does not appear to be realistic. Only prolonged research and experimentation could determine the correct level at which such

a lake should be dosed. The above estimates serve only to indicate the orders of magnitude of such an undertaking. Since the fish production of the lake is not well known, and since it may not yet be stable, attempts to control or augment it with fertilization are out of place at this time at least. The time of year when fertilization might be attempted is also controversial. Maximal nutrient and water inflows (nearly 90 percent--FAO, 1971) occur from about August to November, and the major slack period is December to February for algal growth. Biswas (pers. comm.) suggests that adding fertilizer just before the algae are about to flourish might alter the osmotic conditions unfavorably and so inhibit growth; on the other hand, nutrients are highest at other periods. Also, the pH of the lake has gradually declined from neutrality around 1968-1970 to a present level of about 6.6 to 6.7. Thus, the lake's buffering system is poor, probably related to decreased alkalinity or nutrient level, and the principal fertilizer might have to be lime to correct this (Biswas, pers. comm.).

Although little is known about how explosive waterweed growth occurs, there is a real danger of a renewed weed problem following fertilization; and also a build-up of weed-associated insect and mollusc vectors with consequent health problems. It appears that either a new habitat or a disturbance in the community allows water weeds to spread. Despite sudden nutrient enrichment following impoundment of the Volta

(Lawson, 1964, 1967), the outbreak of Pistia was minor and has since decreased. It seems to be limited to inflowing stream areas by the need for nutrients as well as for shelter (Hall, pers. comm.). Fertilization could change this stable situation. All these factors point to the inadvisability of attempting lake fertilization at this stage, a viewpoint held by numerous scientists in Ghana.

Summary

The lake is showing declining productivity, in part as a natural consequence of the artificially high peak following impoundment, but in part because of the poor rains of the past three years, 1970-1973. Changes in this variable factor could significantly change the level of the fisheries. Although nutrient levels and phytoplankton counts are low, productivity of the lake is moderate, and is dominated by the littoral and the shallow flooded trees, coated with aufwuchs.

The lake is best treated as two entities, a northern riverine area and a southern deep lake with lower productivity because of the lessened influence of the shoreline. Fish stocks are different in the two areas, and catch methods also differ. In the south the open-water clupeids support their chief predator, Lates; this situation merits further study as it shows signs of possible overfishing.

The drawdown area is already important and will become more so, in terms of fish feeding and nursery areas, among the water-tolerant grasses and Polygonum. Fertilization of this area, if farmed, might also enhance lake productivity.

It would be worthwhile to investigate the potential of artificially increasing stocks inshore by ponding off shallows for fish-farming, or by placing bundles of brush as aufwuchs surfaces and refugia, in cleared and heavily fished areas. These measures could increase the catch and help reduce the indiscriminate pressure on the native stocks.

Research Problems

Echo-location of fish stocks might be useful in open-water research; a small expenditure to repair the unit on board the research vessel Tilapia is recommended, as it has reasonable discrimination (i.e., Reynolds, 1971).

The species problem seems quite acute in tropical Africa. The tendency to "lump" species into known brackets may lead to wrong assessment of the future roles of a species in an impoundment. Alestes baremose, for instance, feeds differently in Volta and West African rivers than in Chad and East Africa; its specific identity has not yet been questioned, but to assume that it would eat zooplankton in the Volta would have been quite erroneous.

In Volta research there has appeared to be much duplication of effort--limnological work, in particular. In planning international participation, careful consideration is needed of national staff and work already in progress, for they function much less expensively than an international body. Facilities and physical plants are already present, and the standard of living is more in tune with reality. If funds are to be provided, they should be to augment these institutions and provide only staff and equipment without which an essential project would remain uninvestigated. For instance, several scientists have expressed their regret that the Smithsonian had not sponsored more extended periods of study of real lacunae in our knowledge of the lake.

Two items of controversy remain on the Volta: the weeds and the flooded trees. Without going into historical details (e.g., Ram, 1968), it appears that the flooded trees have enhanced productivity of Lake Volta considerably, though there is room for their clearance inshore near villages and landings. Aquatic weeds also enhance productivity, but in Volta they were unfortunately associated with a peak of Bulinus bilharzia vectors. The Ampem weed eradication experiment was important in showing how little the two factors were related. Similarly, experiments with the semi-aquatic drawdown vegetation should be encouraged to maximize its usefulness to the fish as shelter or as food.

There are several other research projects which merit consideration on the Volta. These include:

1) More detailed studies of zooplankters, their patchiness and reasons for their localization; also investigations into what organisms, if any, utilize the abundant rotifers.

2) Studies of drowned Vossia and Polygonum beds to assess their quantitative contribution to productivity, in terms of biomass of aufwuchs, amounts of leaf material lost to browsers, and biomass of emerging Povilla and chironomids. If possible, estimates should be made of Povilla vulnerability to fish as compared with vulnerability in areas of flooded trees , etc.

3) Studies of feeding patterns of a fish species at different lake locations, and at different times, to throw possible light on changes in abundance. If possible, rotenoned or electrofished specimens should be used, as gill-netting allows digestion of gut contents before the samples are collected.

4) Studies on the rate of decomposition of trees in the lake, both north and south and in detail, to supplement the present sketchy observations.

5) Investigations of seasonally flooded fish ponds created by damming of shallow bays. This is a major project which might be undertaken in conjunction with rice culture, or as a discrete effort. Studies could involve the use of bundles of Polygonum or Vossia as shelter and food sources for enhancement of production.

6) Fish stock assessment is still a major problem, and is being actively worked on at present. Research should be encouraged which links limnological parameters with fish stocks present, as initiated by Ryder and pursued by other workers (e.g., Vanderpuye). In a large impoundment where the major nutrient input is dependent on the inflowing rivers, levels of these, or of their total dissolved solids, might show good correlations with experimental catches, and thus relative stocks could be monitored.

8. Water Supply and Waste Assimilation Aspects of Volta Lake

Introduction

Volta Lake is an environmental resource of enormous potential value to the people of Ghana. Benefits obtained from hydro-power production, lake fisheries, and water transportation have already begun to offset the considerable social cost of the project. While these resource services will continue to be utilized in the future, the net returns from the use of the lake may be increased by exploiting additional resource services. Among those under consideration are the subjects of this section: water supply services to small and large human settlements, and waste assimilative services. A proposed framework is outlined for consideration of the subject matter, aspects of water supply and waste assimilation services are reviewed, and lastly, conclusions and recommendations are presented.

The discussion and recommendations which follow derive from those data now available in the published literature and in the files of government agencies. These data were reviewed during a three-week period in July, 1973. The author also met with Ghanaians working on water resource problems and visited

several sites on south Volta Lake. These visits and interviews were invaluable in placing disparate bits of information into an appropriate context.

Managing Environmental Resources

Water supply and waste assimilation are only two categories of possible uses of the Volta Lake resource. A discussion of these uses is best organized within a framework which places them in a larger context that includes related uses, notably the generation of electric energy. This section sets forth such a framework, namely a resource management model of the asset utilization type (e.g., Mohring and Boyd, 1971) and discusses its application to the planning and management of the various uses of Volta Lake.

Characteristics of environmental resources.--It is convenient to think of a major environmental feature (such as Volta Lake and its associated shorelands) as a single environmental resource capable of supporting many inidividual resource services. The resource services ordinarily interact, such that the use of one service may alter the available supply of another at the same time, or at a later time. Further, many resource services exist as common property; they are available to all users without cost (for the service itself).

It is these features which make the effective management of environmental resources a major challenge to any society. For example:

a) Since resource services are related, the unconstrained use of one may seriously reduce the availability of others, perhaps sacrificing high-value uses for the sake of small increases in the value of the over-exploited use.

b) Where resource services are common property, it may not be feasible to effectively regulate use, no matter what the desired level.

The Volta Lake is no exception to these generalities. Many resource services are available, including the potential for hydropower production, for various types of water supply, for fish production, for waste assimilation, for water transport, for recreation, etc. Some of these services have important common property aspects: the fish production capability of the lake is effectively available to all, and deliberate regulation of the level of fish harvesting would be exceedingly difficult.

It is also evident that the services offered by Volta Lake interact. The most obvious example is the interaction between certain water supply services and the generation of electric energy. If water is to be diverted to users outside of the lake catchment area, for example, it can be seen that increasing the use of hydropower services (increasing electric generation) would reduce the water supply service by reducing the quantity of water available for diversion. This particular

interaction is bilateral--increasing the use of the water supply service decreases the supply of water available for the generation of electric energy.

Other linkages exist between waste assimilation and fish production, between waste assimilation and water supply, etc. The practical implication of these observations lies in the fact that the full exploitation of a single resource service may well reduce or eliminate the potential availability of other services. For this reason it is not possible, except in rare instances, to simultaneously maximize the output of each service, even if unlimited supplies of other factors (labor, capital, etc.) were available to do so. When the quantities of capital and skilled manpower available to plan, implement, and manage the use of environmental resource services are themselves limited, as they certainly are in the lesser developed countries, the problem acquires additional dimensions.

To summarize this characterization of the problem, a resource such as Volta Lake can be described as a single environmental resource capable of providing a number of resource services. Certain of the resource services may exist as common property. Linkages occur between the services such that the use of any one of them may reduce the available supply of another, concurrently or at a later time. Any plan for exploitation of these services must take account not only of the net benefits to be obtained from various levels of use of each service, and of interactions between services, but of the limited supply of

capital and human resources required to plan, implement, and manage the resulting scheme.

Resource management.--Once the resource services have been identified, and the linkages between them determined, it is possible to consider optimal use of the environmental resource. The term "optimal" is employed here to describe the particular pattern of use of the various resource services which would be preferred by the people of Ghana (taken collectively) over all possible alternate patterns. To say that optimal use of Volta Lake had been achieved would be to state that no change in the pattern of use then in effect could possibly produce a result which would be more satisfactory to the nation. Obviously, such a situation is not likely to occur, given incomplete knowledge and fallible human judgement, and still less likely to be recognized should it serendipitously appear. Still, investigations of the characteristics of optimal solutions to resource management problems are invaluable in identifying issues, evaluating proposals, and developing management criteria.

It can be postulated that an optimal solution exists for the Volta Lake management problem; it is that pattern of service use, now and throughout the foreseeable future, which guarantees the most satisfactory possible result. In order to learn the nature of such a solution, it is necessary to specify an objective function, a statement of society's goals in managing the resource. For example, the objective may be to

maximize the total benefits to society, net of opportunity costs associated with the quantities of skilled manpower and capital diverted from other activities.

The objective function is maximized subject to certain technical constraints:

a) The relationships between the level of use of each resource service, the required quantities of labor and capital, and the resulting benefits to society.

b) The relationships which link the various resource services.

Further constraints may be required to complete the statement of social goals:

c) An upper limit on the quantity of offshore inputs may be set.

d) Where certain resource services are considered to have national importance beyond that implied by their economic value (some part of the possible hydropower capacity, for example, or certain wildlife refuge schemes), this determination may be reflected by suitable constraints setting lower limits on affected activities.

e) Where a finite planning horizon is employed, constraints may be required to protect the residual value of the resource at the end of that period.

f) Limitations on supplies of certain skills and of investment capital may be recognized by appropriate constraints.

Solution of such a maximization problem yields a set of marginal conditions which can be used to test whether any actual or proposed pattern of resource service use is consistent with optimal utilization of the resource. In this way it can be determined whether any proposed use of such a service as water supply is desirable. If the problem has been properly formulated, this determination takes full acount of relevant national goals and policies, of the manpower and finances required to implement the proposed use, and of the impact of such use on the supplies of other resource services.

These paragraphs have presented the essence of multiple-purpose resource planning and management. The procedure outlined is comprehensive, demanding, and requires consistency with policies and goals being formulated at the highest levels of government. But it offers the opportunity of increasing the return from a limited supply of capital and skilled manpower, certainly an important consideration in a society where supplies of these scarce inputs fall short of needs.

The Volta River project.--The Volta River Project may be considered within the context of Ghana's total environmental resources. It can be postulated that presently Ghana does not have the ability to exploit the potential value of her natural environmental resources. For this reason, when finances and talent are committed to a particular project (such as the Volta

River Project), it is essential that the largest possible returns be obtained from that commitment. Although this result requires, in every instance, a multiple-purpose orientation, it may, in specific cases, obtain from what appears to be a single-purpose plan. Among the circumstances which may give rise to this outcome are:

1) Costs of planning and implementation may exceed expected benefits for all uses except the principal one.

2) The planning and implementation of the principal use at the lowest feasible level may exhaust the available supplies of talent or capital, or both.

The evolution of the various Volta River Project studies shows that there was a shift in resource management emphasis from single-purpose to multiple-purpose, followed by a return to single-purpose management. The first investigation of the scheme was commenced in 1944 by a South African engineer, C. St. John Bird, on behalf of West African Aluminium, Ltd. His report (Bird, 1949) recommended the construction of a dam, hydroplant, and aluminium smelter at Ajena, to be serviced by a port at Ada. Although improved water transportation was mentioned as an incidental benefit, the development of the project had a single purpose--the production of electric energy for the smelting of alumina. This result is consistent with the probable function of West African Aluminium, Ltd.--to

maximize expected profit from the manufacture of aluminium. Any other services which the project might be capable of providing are not likely to produce revenue for the company, hence they do not appear as part of the company's preferred strategy.

At about the time Bird's report appeared, the Government of the Gold Coast Colony engaged a British consulting firm, Sir William Halcrow and Partners, to prepare an independent assessment of the potential for development of the Volta River Basin. The resulting report (Halcrow and Partners, 1951) gave evidence of a multiple-purpose planning approach. Among the resource services which the engineers thought worthy of consideration were:

1. Hydropower production.
2. Water supply for irrigation.
3. Water transportation.

Other matters, such as the effects of the resulting lake on public health, were discussed but not reckoned as project costs or benefits. The broader outlook of the Halcrow report, of course, reflected the desire of the colonial government for maximal returns for the level of investment contemplated.

By this time, interest in the project led to the formation of the Volta River Project Preparatory Commission in 1953. The Commission was directed to survey the project as a whole and to report on its feasibility, which it did in 1956

(Volta River Project Preparatory Commission, 1956). With respect to Volta Lake, the Commission limited its published analysis to discussion of the potential for production of electric energy, and the various financial and social costs associated with that activity. The planning of the Volta River Project had once again focused on a single purpose. This orientation was retained throughout the Kaiser Reassessment Study (Kaiser and Company, 1959), and the actual construction of the dam and subsequent formation of the lake.

There can be little doubt that this seeming retreat from a multiple-purpose approach reflected a concern, on the part of both the Preparatory Commission and the Kaiser Engineers, about the ability of the country to implement a more ambitious scheme. Investment capital was in short supply, as was the planning, design, and management talent necessary to successfully complete a complex, multiple-purpose development. Consequently, the activity which showed promise of producing the largest net gains for the nation--the generation of electric energy for the aluminium smelting industry--was selected as the major purpose of the project.

It is quite possible that, given prevailing conditions, an explicit multiple-purpose approach would have led to equivalent conclusions. The constraints on money and manpower were real and, after including the element of risk present in all such projects, it may have developed that no competitive use of the lake could have been provided for without producing

costs in excess of the expected benefits. At any rate, the Volta dam was constructed for the single purpose of generating electric energy, without structural provision or earmarked capacity for other purposes.

But once the lake was filled, the hydro-plant operating, and the aluminum smelter constructed (all completed by the late 1960's), circumstances began to change. Much of the uncertainty which entered heavily into the planning process was now gone, the costs became known, the operating characteristics known, and the future closer, so that revenues are now being generated and debts being repaid. Many of the skilled Ghanaians who were occupied so heavily during the early phases of the project can now hand their more routine operating duties to others and turn to more challenging assignments. In short, it is now possible to consider whether multiple-purpose management of the Volta Lake, a single-purpose development, might not increase the value of this resource to the nation.

As early as 1964, Abhyankar noted the possibility of multiple-purpose management (Abhyankar, 1964). The Volta River Authority is already actively promoting increased uses of services such as water transportation, drawdown agriculture, and fisheries, both on its own account and through the Volta Lake Research Project. The remainder of this report will discuss two classes of resource service which are not now the subject of systematic investigation or development--the water supply and the waste assimilation services of Volta Lake.

Water Supply Services

The Volta Lake basin is capable of providing at least three general classes of water supply service in the form of withdrawals, as well as certain specific services within each class.

a) Water withdrawals from tributary streams (upstream of the lake proper).

b) Water withdrawals from the lake itself.

c) Water withdrawals from the Volta River downstream of the Akosombo Dam.

Each class is discussed in separate sections below. Specific water supply services are defined by the exact location of withdrawal, the time-pattern of withdrawal, the fraction of withdrawn water returned to the basin, etc.

The principal, and usually decisive, consideration in withdrawals is the distance between the point of use and the possible withdrawal site. Water is expensive to transport over long distances and the nearest withdrawal site is likely to be heavily favored. Other factors may modify this conclusion, including considerations of supply reliability and elevation. When the proposed use must have reasonable protection from drought, supply from the lake itself may be preferred over nearby tributaries. Conversely, a source at a higher elevation may reduce pumping costs. This last point deserves some expansion.

Withdrawal energy requirements.--While water withdrawals from the lake obviously compete with the generation of electricity, withdrawals from below the dam may compete even more. Presently drinking water for Accra and Tema is withdrawn at Kpong, ten miles below the Akosombo Dam, and pumped to the necessary elevation for conveyance to these centers.

The 1951 Halcrow report recommended that irrigation water be obtained at the same location and pumped to elevation 230 feet (70.1 m) O.D. for transport to the Accra plains. The later Kaiser irrigation study (Kaiser Engineers and Constructors, 1965) proposed a similar scheme, although advocating direct withdrawal from the lake after seven to nine years.

The amount of energy consumed in pumping for present and potential withdrawals is determined largely by efficiency of hydropower generation and of the use of electricity for pumping. The water from the lake falls from an average elevation of 264 feet (80.5 m) O.D. to the tailwater elevation of 47.5 feet (14.5 m)--an average fall of 216.5 feet (66.0 m). The falling water drives a turbine, which is coupled to an electric generator. The electric energy thus produced is connected to energy users through transformers, switches, and transmission to pump lines. Water withdrawn immediately below the dam to a higher elevation will require energy to drive the pump.

If the turbine and generator have a combined efficiency of .87; the switches, transformers, etc., an overall efficiency of .98; and if the electric motor operates at an efficiency of .95 and the pump at .85; then the comp. a system is approximately 70 percent efficient. That is, one gallon of water falling 216.5 feet (66.0 m) from the lake will produce enough electric energy to lift that same gallon of water back to 70 percent of the distance fallen (151.5 feet or 46.2 m). This neglects other sources of energy loss, such as pipeline friction.

If water taken from the tailwater at Akosombo were lifted to 230 feet (70.1 m) O.D. for irrigation of the Accra plains, 1.2 gallons of water would have to be released from the dam for every gallon withdrawn. This is true because the electric energy produced by the release is only sufficient to lift the water back to elevation 199.0 feet (60.7 m). This analysis assumes that the pumping can be done off-peak, so that the hydro-station capacity requirement is not increased.

This example shows that <u>water withdrawn below the dam</u> does indeed compete with electric energy production. The strength of the interaction depends on the elevation to which the withdrawn water must be pumped and on the overall efficiency of the generation-transmission-pumping system. <u>Water withdrawals from tributary streams</u> obviously compete on a

gallon-for-gallon basis with withdrawals from the lake and with the generation of electric energy. Water supply withdrawals from the lake are similarly direct competitors with electric generation. This discussion of efficiency is intended to illustrate some aspects of the comparison among alternate supply points. In an actual comparison, other factors, including relative costs, may be similarly important. Costs will be influenced by demand for various water uses, and the actual level of these uses.

Withdrawals from tributary streams.--Withdrawals from the rivers and streams tributary to the Volta Lake are of interest because they reduce the quantity of water available for other purposes in exactly the same manner as withdrawals from the lake itself. Of the 398,373 km^2 of drainage area in the entire Volta River basin, only 42 percent (165,913 km^2) lies within Ghana (Krishnamurthy, 1964). Although plagued by unavailable, incomplete, incorrect, and inconsistent historical data, hydrologists in the Hydrological Survey Branch, Public Works Department, have assembled streamflow records which suggest that the mean annual flow of the river at the dam site was about 26.6 km^3 prior to construction. The Nathan Consortium study (1970) gave the mean annual flow from the entire basin at 37.0 km^3. It appears that evaporation from the lake surface is nearly balanced by the gain due to rainfall upon the surface. It can be concluded that, on the basis of available records, mean annual net inflow to the lake from all sources is at least

36.0 km^3, probably more. However, as mentioned in earlier sections (pp. 43, 44) variations from the mean are great, and can lead to serious problems or crises in water management.

A map issued by the Hydrological Survey Branch indicates that within Ghana, water is now being withdrawn from tributaries of Volta Lake at 19 points, with schemes proposed for five more. No information is available on the total quantity of water thus withdrawn, on quantities likely to be withdrawn in the future, or on present and contemplated withdrawals in other countries drained by the Volta River (Mali, Upper Volta, Togo, Dahomey, Ivory Coast). This last point is especially relevant in view of the continued drought in several of these countries (Annan, 1973). In short, knowledge of the surface water balance of the Volta Lake drainage is scant.

Water level gages are now positioned so as to monitor, with few exceptions, the inflows to Ghana from other countries, and the inflows to the lake itself. The importance of maintaining and augmenting this system, and of obtaining accurate, up-to-date rating curves for each gage, has already been emphasized. The data obtained, together with associated rainfall measurements and improved records of surface water withdrawals, are essential to rational management of the lake resource.

In the absence of such data, some appraisal of the significance of upstream withdrawal is necessary. Barring irrigation

projects and industrial development (neither of which appear imminent in this area), the quantities of water likely to be withdrawn from tributaries in the medium-run future appear minor. A development plan for the lake which ignores the possibility of significant withdrawals at some time, however, would be short-sighted.

Withdrawals from the lake.--Water withdrawals from the Volta Lake proper might be divided into three categories:

1) Withdrawals for human settlements located within the lake drainage basin.

2) Withdrawals for irrigated agriculture or industry located within the lake drainage basin.

3) Withdrawals for human settlements, irrigated agriculture, or industry located outside the lake drainage basin.

These categories will be discussed in turn.

1) Withdrawals for human settlements in the lake drainage basin.

Although the Volta Lake catchment includes almost 70 percent of the land area of Ghana, the communities most likely to consider it as a source of water supply are located on, or very near the lake shorelands. These water-oriented communities consist of established towns and villages which existed prior to the formation of the lake (sometimes called "host"

communities), the 52 resettlement villages constructed to house families displaced by the lake, and numerous spontaneous and short-lived villages of fisherfolk, located at the shoreline itself. It has been estimated that about 100,000 persons live in up to 1,000 communities located on or near the shores of the lake (C.R. Jones, pers. comm.).

All of the resettlement villages and many of the host communities have had provisions made, at one time or another, for community water supply. These provisions are ordinarily based on boreholes, and distribution facilities range from hand-operated pumps at the wellhead to diesel-powered pumps feeding a number of public taps. The author visited six such installations. Only one appeared to be operating properly.

The water supply system at the Ampem resettlement village was designed to withdraw surface water from a small tributary of the lake. At the time of the inspection (July, 1973), the stream was entirely devoid of surface or subsurface flow as it had been, according to local reports, for more than two years. Vegetation in the vicinity showed clear signs of prolonged drought. In any case, the pump's Diesel engine had been partially dismantled and the pushrods were missing. Villagers were carrying water from the lake.

In another community (Fesi Kpandu resettlement), a geared hand pump and sections of casing (totalling about 20 m) had been removed from a borehole and a lever-action hand pump

installed. The well was producing very turbid water, suggesting that surface run-off flows rather directly to the borehole. The town manager reported that the well is dry at all times except for several days after each rainfall. Since the inspection was made during the wet season, the well was in use, but at other times water is obtained from unprotected springs more than one mile distant.

Other systems examined suffered from non-functioning Diesel engines, broken pipelines, and broken taps at the community standpipes. In one case, in fact, only one tap could be found in working condition throughout an entire community. Inspection of the pump operator's log for the single water system which was found in working condition (Tepo resettlement) disclosed evidence of delays ranging from ten days to three months before reported deficiencies or failures are corrected. Conversations with other individuals familiar with the lake area indicated that the observed conditions are not atypical.

It appears that the great majority of the lake area's 100,000 residents are effectively without community water supply. At each of ten shoreline locations where the author was able to spend some time, persons were observed carrying water from the lake. In most cases, this chore is performed by young children of both sexes and by adolescent girls, and less often by adult women. Most persons who are active in the study and treatment of schistosomiasis in this area agree that

the water-carrying activity is an important opportunity for infection. It is also possible for cercariae in drinking water to penetrate the mucous membranes of the mouth and throat, but the significance of this infection route is unknown.

It is only natural, under the circumstances, to become frustrated with the performance of the existing water supply systems, and to propose construction of new systems, perhaps using lake waters as a source. In fact, this suggestion was heard during more than one conversation. It should be emphasized that the existing systems do not in any way appear faulty in design or concept. The difficulties stem from the apparent absence of any institution or organization capable of maintaining the installed equipment in operating condition. Following the conveyance of official responsibility for these systems from the Volta River Authority to the general government in 1966, operating responsibility for individual systems (in resettlement villages) became lodged, at different times and places, with either the Local Councils or the Ghana Water and Sewerage Corporation.

The Local Councils clearly lack the manpower and the finances to discharge a responsibility of this magnitude with anything approaching the required standard of performance. The Ghana Water and Sewerage Corporation, which does possess the necessary abilities, has experienced serious logistical problems in attempting to assume responsibility.

Under prevailing conditions and when groundwater is available, surface water systems confer no advantage, but produce increased risks. If lake water is considered as a source, turbidity and bacterial contamination must be reckoned with. Even if turbidity could be ignored, the most elementary public health precaution would require disinfection, probably by chlorination, of all water pumped. If the chlorination equipment is maintained in the same fashion as existing equipment, failures can be expected. Should the rest of the system continue to function, the dependence of an entire community on an untreated supply drawn from a single point might well result in a risk of waterborne disease even higher than that associated with present practices.

It is the hope of the Ghana Water and Sewerage Corporation that nearby communities can be eventually joined by water transmission lines, and that the number of source and treatment works can thus be greatly reduced. This approach is consistent with the proposed "National Water Grid" and it may be that it would, if implemented, permit improvements in the standard of maintenance. On the other hand, if connecting pipelines are too frugally designed and installed, the reliability of the individual systems may fall still further. A successfully interconnected series of villages might, under some circumstances, permit the installation and operation of more sophisticated treatment works and, provided reliable operation is actually achieved, allow consideration of the lake as a

source of supply. At the present time there is no indication that this alternative will be either feasible or desirable.

In the discussion, it has been tacitly assumed that a negligible fraction of the water withdrawn for use in lake-oriented communities will be returned to the lake. The types of water use now practiced in these communities, and the method of liquid waste disposal, virtually assure the validity of this assumption. A very great change in the standard of living in villages and small towns would be required before significant quantities of waste water would be generated, and even then it is doubtful how much of the quantity generated would reach the lake.

2) Withdrawals for irrigation and industry in the lake basin.

Large volumes of water could be withdrawn for irrigation or industry. Proposals have been advanced for large-scale irrigation of the Afram plains area, and for the siting of one or more relatively modest fish processing plants. As time goes on, particularly if some schemes are successfully implemented, more and more proposals of this type can be expected to appear. In every case where withdrawals of water from the lake exceed returns of used water to the lake or its tributaries, the supply of water available for electric power generation is reduced. So long as the supply does not fall below the quantity actually demanded for power generation, no conflict exists.

The existing hydropower facility is capable of using virtually all the expected annual inflow to the lake, and demand for electricity is growing steadily. The Volta River Authority will eventually have to either prohibit withdrawal of any water that is needed for electric generation (to the maximum extent of its authority to do so), or take a multipurpose management approach and permit certain withdrawals, even though they reduce generation.

In the first alternative, the management of the lake remains essentially single-purpose, as it is at the present time--secondary uses of the lake are permitted only so long as they do not compete with the primary use. The enabling legislation of the Authority, the Volta River Development Act, specifies a number of purposes other than power generation, but they are all clearly non-competitive (fishery development, water transportation).* Since it seems clear that no possibility of interaction was anticipated by the framers of the act, these purposes can be considered secondary to the generation of electric energy.

The second alternative presents a more difficult management problem. Because it is possible, with adequate planning, to produce electric energy elsewhere (perhaps by thermal plants located on the Lower Volta River), reductions in the supply of water available for generation can be contemplated.

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*Laws of Ghana, Act 46, Volta River Development Act, 1961 (as amended by Act 95, 1962).

3) Withdrawals for uses outside of the lake basin.

The final category of lake withdrawal is that intended for human settlements, industrial uses, and irrigated agriculture located outside the Volta River basin. Compared to the category just discussed, this possibility has two distinguishing characteristics: (1) no return flows will reach the lake, and (2) proposals for large-scale withdrawals seem much more likely.

The population center of Accra-Tema, 60 miles south of the lake is the largest in Ghana. In 1970 Accra had 680,000 inhabitants and was growing at a ten-year doubling rate. Tema, although smaller with only 100,000 was growing even faster at 12 percent per year (World Bank, 1971). According to the Nathan Consortium for Sector Studies (1970), the combined per capita water use of these two centers was 136.1 liters per day, while the World Bank (1971) estimated 122 liters/capita/day. Even at the lower use rate, this is roughly five times the water consumption rate of the lake's 100,000 dwellers. Most of the country's manufacturing is located in the Accra-Tema area, and nearby is the Accra plains area, probably the most attractive venue for large-scale irrigated agriculture. These circumstances suggest that major diversion of Volta Lake waters outside of the basin and to the south may well be considered in the near future.

In this event, the decision-making process should follow the same outline given above for irrigation and industry located

within the lake basin. Careful forecasts must be prepared, analyses performed, and the expected degree of interference determined. With this information in hand, the management stance taken by the Volta River Authority will determine the nature of the decision taken.

4) Management implications of lake withdrawals.

When net withdrawals reach the point where some electric generation must be foregone, the last units of water used acquire an opportunity cost. That is the full social cost of generating the displaced increment of electric energy at another location. So long as the net social benefit from the water use exceeds this opportunity cost, in this very simple example, it is in the national interest to permit the withdrawal, and to provide the required auxiliary generating capacity. The network of interactions among the lake services extends, however, to more activities than water withdrawal and electric energy generation. For this reason, more data and more elaborate mathematical models are required to evaluate proposals.

Nature of demand and growth of electric power needs are important planning elements. Demands for services tend to be seasonal, and to grow over time. The volume of the lake is sufficient to dampen the effect of seasonality for most uses, but excessive reliance on this feature leads to more complex operating rules for releases at the dam, increased

risks of inefficient operation (unnecessary loss of water), and increased competition between uses. Growth over time is also important, as supplemental generating capacity must be programmed and constructed at the "right" time--not too soon and not late--to avoid excessive costs. Up to the present time, it has not been necessary for any agency concerned with Volta Lake to study, except in a superficial way, the future demands for its services. Such studies are essential to true multiple-purpose management.

It will be necessary to prepare a careful forecast of the net withdrawals expected over time. Equally careful forecasts must be prepared of expected water releases for electric generation and of the level of any related activities (other lake withdrawals, upstream or downstream withdrawals, etc.). Stochastic hydrology techniques can be used to simulate sets of likely future inflows to the lake and these, in conjunction with simulation of appropriate operating rules for scheduling spills, will determine the expected degree of interference, if any, between uses. Should interference appear, the management stance of the Volta River Authority (single-purpose vs. multiple-purpose) will determine the next step. Any proposal for significant withdrawal of irrigation waters from the lake will be quite likely to create interference. Large industrial uses are not now planned, but could be considered in the future when other elements of the country's infrastructure are better developed.

Withdrawals from the lower Volta River.--The demand for withdrawals from the Volta River below the Akosombo Dam, for use within or outside of the basin, is virtually identical to that described in the immediately preceding paragraphs--the community, industrial, and agricultural water demands of southeastern Ghana. It differs only by reason of water availability and cost. Where a heavily seasonal use is anticipated (e.g., irrigation), withdrawal from the lake, using its storage capacity to accommodate peak flows, may be convenient. On the other hand, the construction of water conduits to the lake may greatly exceed the cost of source and transmission works required for river withdrawal.

It has already been pointed out that withdrawals below the dam appear in the form of increased electric generation requirements, due to the necessary pumping. Should a single-purpose management stance preclude any direct withdrawals from the lake because of interference with electric generation, unregulated use of the downstream alternative may well result in even less electric energy available to other users.

Since the lake/downstream choice presents itself to the user classes most likely to exert the greatest demand on the water supply service of the Volta basin (the urban-industrial-agricultural complex of southeastern Ghana), it is suggested that a multiple-purpose management approach is not only essential to economic efficiency and orderly development, but probably unavoidable as well.

The proposed lowhead dam at Kpong offers an excellent opportunity for design in the context of multiple-purpose plan covering the entire catchment area. It should be noted again, however, that most of the information requisite to such an approach--demand forecasts for various resource service uses, statement of national water resource development goals, knowledge of basin water balance, etc.--is not available at this time. A commitment to a more rational approach must start with the preparation of this information.

Waste Assimilation

Volta Lake, taken as a whole, possesses a very large capacity for assimilating liquid wastes, whether from human settlements, industry, or irrigated cropland, without noticeable effect on the supplies of other resource services. Containing more than 160 km^3 of water at the maximum regulated stage, the lake has vast dilution potential. The tropical climate insures that decomposition of organic wastes will tend to occur at a high rate year-round. Even nutrients released from decaying organic matter, and contained in irrigation return flows, storm water run-off, and certain industrial discharges, are not unwelcome, given the relatively poor nutrient status of the lake's waters. In fact, it is difficult to conceive of the generation of a volume of waste which would, if spread uniformly throughout the lake, cause any significant change in the value of the lake to other users.

But wastes are not distributed uniformly throughout a body of water--they enter at specific points and it is in the vicinity of these points that interactions between waste assimilative services and other services occur. Thus it is quite possible for a specific discharge to cause serious deterioration of the water immediately surrounding its outfall, no matter what the "assimilative capacity" of the lake as a whole. This is particularly true if the discharge point is in a sheltered cove, a shallow area, or other location where mixing is minimal.

Waste assimilation, then, is a local phenomenon, and must be investigated on a local basis. Generalizations concerning the waste loading of the lake as a whole have no meaning except where the entire lake becomes seriously polluted, an unlikely event. The possibilities for local pollution will be analyzed by discussing, in turn, wastes from human settlements, cropland, and industry.

The discharge of human and household wastes into watercourses within Ghana is very much the exception rather than the rule. The only city with essentially complete sewerage is Tema; Accra is only partly sewered at the present time (C. K. Annan, pers. comm.), although sewerage system construction is underway. Around Lake Volta towns and villages rely almost entirely on pit latrines, permanent latrines, and septic tanks for other household wastes. In some cases,

household wastes (wash water, etc.) may reach the lake or its tributaries, and much washing is done in the lake itself. The soap and other materials thus contributed appear to have little effect on aquatic conditions. Given these practices and the prognosis for growth and economic development in the lake area, there appears little chance that significant quantities of liquid waste from human settlements will be discharged into the lake in the near future. Two related topics are worthy of comment, however: human waste disposed at ferry ports and urination in the lake.

At ferry crossing points, large numbers of people wait for some hours, often overnight, to board a ferry to cross the lake. Although privies are provided at some points, they are necessarily some distance from the water's edge, and many people are believed to dispose of human feces, as well as garbage, etc., in or near the water. The writer visited one such crossing point (Adowso), but was unable to observe evidence of feces deposition. Some garbage was visible along the shore, and in the wake of the ferry boat itself. No changes in aquatic conditions have been observed in these areas thus far (M. A. Odei and A. K. Opoku, pers. comm.), but they should be kept under continuing scrutiny.

The second topic concerns the practice of urinating whenever and wherever the need occurs. This behavior can be widely observed in both urban and rural settings. Ordinarily, indiscriminant urination is neither a water quality problem,

nor a public health threat. But the practice takes on special significance where urinary schistosomiasis (S. haematobium) is endemic. The transmission of ova from the human host into the aquatic environment, via urine, is a critical link in the propagation of the disease, and offers one of the few possibilities for effective control (C. F. Jones, pers. comm.). Unfortunately, the cessation of urination at the lakeshore is not likely to come about as a result of waste management policies--it requires a basic behavior change. It seems evident that a thorough and continuing program of public information and education will be required to eventually correct this dangerous practice.

While human wastes have not been found to pose a threat to aquatic conditions in the lake, there can be no such assurance in the cases of industrial and agricultural discharges. Almost any water-using industry which happens to locate on the lake shoreland is capable of discharging wastes which would cause local deterioration of water quality. There is no experience with irrigation return flows in the Volta area but, depending on the type of irrigation, on agricultural practices, and on soil conditions and type, return flows may contain dissolved salts, nutrients, or toxic chemicals, which, if concentrated in a small area of the lake, could cause unwanted effects.

Agricultural waste waters containing relatively persistent and/or toxic pesticides may create serious problems

locally, if used in connection with drawdown agriculture. The adverse effect on certain drawdown crops of the residues of certain herbicides tested for water weed control has been noted. Similarly, careless use of organochlorine insecticides in drawdown areas could have damaging effects on the lake's biota. The long half-life of these chemicals makes them a problem even if used at points within the basin that are distant from the lake. They may be carried to the lake in solution or adsorbed to sediments, and thereafter enter the food chain, as has been noted elsewhere in the world in fresh water lakes. This potential problem is magnified by the increasing importance of the drawdown zone, where sediments are captured by water weeds, and which constitutes nursery habitats for many fish.

No statement can be made concerning the importance of these potential discharges in the absence of forecasts of industrial and agricultural activities at specific locations. Properly managed, there is no reason for problems to arise from the activity levels which might reasonably be forecast. Since there exists no provision for management of any kind, however, there may be some cause for concern.

Managing waste assimilation services.--In theory, waste assimilation is a service of the resource competitive with other services such as fish production and water supply. If, for example, an industry is allowed to discharge large quantities of untreated organic waste, the quantity of fish

available for harvesting in the vicinity may decrease, the quantity of water suitable for withdrawal may be reduced, etc. Such a practice may be tolerated, however, where the value to the nation of permitting the industry to continue the untreated discharge exceeds all associated costs to other users of the lake. Even in this case, there are also serious equity problems which need examination. Although the industry's gain may exceed the fisherman's loss, the fisherman is placed in the position of subsidizing the industry by giving up a portion of his catch so that the discharge may continue.

The proper approach to waterborne wastes is the comprehensive, multiple-purpose approach to the management of the entire lake system. This approach is probably not justified at the present time. Still, unrestricted discharges should not be permitted. The problem can be dealt with by formulating some general guidelines for use in evaluating individual instances. The guidelines might permit discharges up to the point of just perceptible interference with other users of resource services. The responsibility might well be placed on each individual discharger to demonstrate that he is not exceeding the guidelines with respect to any other user. He would then conduct the necessary studies and present the required analyses justifying the discharge level requested. In this way, some reasonable balance can be maintained between the use of the waste assimilation services of the lake and the

use of the other services affected by that use, at least until the day that more effective regulation becomes feasible.

Conclusions and Recommendations

This section has examined two groups of resource services offered by Volta Lake--those associated with water supply and with waste assimilation. In both cases, the potential for significant future use of certain of the services appears to be present. No significant use of either type of service is made at the present time. The actual level of future use will depend on the management stance taken by the Volta River Authority, and by related government agencies.

It appears, on the basis of this review, that if a comprehensive, multiple-purpose approach to planning and management of the lake resource is not adopted, the result will be a smaller return from the Volta Lake Project than would otherwise be possible. For example, a proposal to divert water from the lake for irrigation of the Accra plains might well, in the absence of active multiple-purpose management, be rejected on the grounds that it reduces the supply of water, hence the quantity of electric energy generated. Yet, if the same quantity of water were taken from the Volta River below the dam and pumped to the required elevation, using electric motor-driven pumps, even less electric energy would be available to other consumers. This conclusion is derived from consideration of physical efficiencies alone--no account is taken of the probable higher cost of river withdrawal.

As long as demands for competitive services of the lake are likely to occur, the Volta River Authority cannot escape the requirement for multiple-purpose management--to do so would be to ignore the opportunity of increasing the total value of the Volta River Project to the nation. A related conclusion is that the Volta Lake cannot be effectively managed independent of its tributary streams and the river below the dam at Akosombo. The water supply and waste assimilation services of these areas are interrelated with those of the lake itself, as is probably the case with other resource services. Planning and managing the lake requires either authority over resource service uses in these other areas, or close coordination with agencies having that authority.

These broad conclusions and the more limited findings noted throughout the report give rise to a number of recommendations, which follow:

1) A comprehensive river basin plan should be prepared and adopted for the entire Volta River Basin. The corresponding management responsibilities should be assigned to appropriate government agencies, including the Volta River Authority. Before such a plan can be prepared, certain information is desirable:

   a) A management objective fully consistent with national goals and policies should be agreed upon.

b) Information should be obtained on inflows, losses, groundwater exchange, withdrawals, etc., so as to obtain a complete water budget for the river and its major branches. The stream gaging program of the Public Works Department must be maintained and augmented to assist in this effort.

c) Careful forecasts should be prepared of the demand for all identified resource services, including electric generation, water withdrawals, etc. These should be based on equally careful forecasts of such economic phenomena as population growth and industrial development.

d) Better mapping is required of the lake area itself. In particular, a more accurate stage-surface area-volume table must be available for flood routing and other management studies. This is probably achieved most easily by photogrammetric methods.

e) The river basin planning activities of the Water Resources Research Unit (C.S.I.R.), should be maintained and expanded. Although now confined to hydrologic aspects of the Densu and Ayensu rivers, this work, if expanded by the addition of suitable staff (including a qualified water resource economist), should result in development of skills and experience invaluable in the recommended Volta basin study.

2) Some means should be found to clearly fix the responsibility for maintaining and operating village water systems on a single agency. That agency should be provided with the resources to properly discharge its responsibilities. This is an urgent problem.

3) Surface water, including lake water, should be considered for water supply to villages only as a last resort, at least until very great improvements are made in the standard of operation.

4) The interconnection of village water systems should be encouraged where indicated, provided it is feasible to do so in accordance with sound engineering practice.

5) General criteria for the use of waste assimilation services of surface waters should be adopted. These criteria would require prospective waste dischargers to show that their discharge will not cause more than minimal harm to other users of the resource. Water quality criteria and standards, and similar measures, will probably be neither feasible nor necessary until a higher level of economic development is attained.

6) A thorough, long-term effort should be commenced promptly to persuade lake-dwellers of all ages, through public information and education techniques, to cease the practice of urinating into, or near bodies of water. This campaign

might employ schools, community development groups, traditional authority, and medical personnel to reach the people. If the program is successful in altering behavior, a major blow would be dealt to the continued spread of urinary schistosomiasis.

7) The areas near ferry crossings should be monitored for evidence of water deterioration or health hazards associated with the careless disposal of human waste and garbage. If a problem develops, appropriate steps should be taken promptly, due to the large number of people using these areas.

8) Although the above recommendations apply to the Volta River Basin, there is clearly a need for a comparable approach to all of the nation's water resources. The following points should be considered:

   a) Comprehensive, multiple-purpose water resource planning must be done.
   b) The objectives stated in such planning must be consistent with the national goals articulated at the highest levels of government.
   c) The twelve or more agencies having water-related responsibilities must be full partners in the planning effort.
   d) Management responsibilities necessary to implement the plan must be clearly assigned to specific and appropriate operating agencies.

9. Biological Control of Schistosomiasis and Other Parasitic Diseases

Introduction

The biological control possibilities for urinary schistosomiasis and other parasitic diseases associated with the Volta Lake were evaluated on the basis of a two-week visit by Dr. L. Knutson in June, 1973. He made two field trips with Dr. Martin Odei, Medical Biologist, VLRP, Akosombo. Observations were made at several places along the southern shore of the lake (from near Kpandu in the east to the ferry crossing at Adawso near the western end of the Afram arm) and at Dove on the Lower Volta River. Numerous scientists involved in the public health and related management problems were interviewed, and their opinions and knowledge were obtained.

This section reviews the major parasitic diseases associated with the Volta Lake, discusses in detail the schistosomiasis disease and the possibilities for its control by biological methods.

The Four Major Parasitic Diseases Associated with the Volta Lake

Onchocerciasis (river blindness).--A black fly, *Simulium damnosum*, is the vector of the parasitic worm, *Onchocerca volvulus*. Larvae of the vector live attached on rocks, etc., in fast-flowing streams, and many of these habitats in the Volta Basin were destroyed when the lake was filled. However, since filling of the lake, habitats have become more favorable downstream of the dam, and disease transmission is more active in some tributaries above the dam. Downstream control has kept the overall prevalence among school children in the endemic Kpong area at 5.3 percent (VLRP, 1972). Basic research is needed on the ecology of black flies: the flight range is unknown, but possibly great. Some disease transmission may be due to black flies flying to settlements over relatively long distances.

Control of black flies in the lower Volta basin was started in 1962. The insecticide used is Arbotine, a 25 percent emulsifiable concentrate of DDT marketed by Shell and applied at 0.1 to 0.3 ppm. Resistance to DDT appears to be developing in the related *Simulium adersi*. The VRA has accordingly changed in 1973 from DDT to Abate, an organophorsphorus pesticide. The harmful ecological impact of DDT was also a factor in this decision. The black fly problem below the dam

may be solved for an additional section of the river by the building of a second dam (planned for 1978) to take advantage of a further 40-foot drop in the Volta below Akosombo. Flooding as a means of control of black fly larvae has been proposed, but this needs more study. The WHO inter-regional black fly program centered in Upper Volta is active to a limited extent in Ghana.

Kuzoe (1970) found one adult S. damnosum with its ovaries infected with a Coelomomyces fungus, another specimen bearing a parasite larval mite, and several specimens containing unidentified protozoon spores. He stated that 40 percent of 45 larval guts of caddis flies (Cheumatopsyche digitata) showed evidence of feeding on Simulium. There has been no study of the application of Coelomomyces fungus on mermithid nematodes as biological control agents in Ghana, and there apparently are no plans to utilize biological control.

Malaria.--The mosquito, Anopheles gambiae, is the vector of malaria throughout much of Ghana. The disease is hyperendemic in Ghana. A certain degree of natural immunity exists; there is a definite, but undetermined mortality due to the disease. Few control measures against mosquitoes are being practiced in Ghana; prophylactic drugs are more or less widely used. There is considerable breeding of mosquitoes in Volta Lake, particularly during times of high water level. Dragonfly (Odonta) adults and larvae feed on mosquito adults and larvae; also lake fishes probably feed on vectors and their larvae.

Sleeping sickness (Trypanosomiasis).--Tsetse flies, principally Glossina palpalis, but also G. tachinoides, are the vectors of Trypanosoma gambiense, the causative agent of sleeping sickness. As these tsetse flies require a high humidity (75-80 percent) and require shade in forests as nocturnal resting sites, the inundation of riverine forests in much of the Volta Basin has greatly reduced transmission of the disease. However, both G. palpalis and G. tachinoides persist in certain fringing forests along unflooded parts of tributaries to the lake. Present control of tsetse flies is by clearing vegetation that serves as resting sites for the flies, and spraying habitats with DDT. Lake shore vegetation is expected to change in time, and perhaps in 20 to 30 years it will provide suitable habitats, especially for G. palpalis in southern areas. Kuzoe (1971) noted, "Human population movements could introduce sources of infection from the northern areas into the southern areas, which had hitherto been free from the disease, and if conditions are right, transmission may occur." The combination of development of lake shore vegetation and lake transportation does indeed seem likely to result in an increase in transmission.

Prospects for biological control of tsetse flies are very limited. The little that is known about their natural enemies was summarized by Jenkins (1964). Research on trypanosomiasis, tsetse flies, and their control is being conducted at the International Centre for Insect Physiology and

Ecology, Nairobi, and is being planned for the new International Laboratory for Research of Animal Diseases, Kenya.

Schistosomiasis (Bilharziasis).--Schistosomiasis is the most prevalent parasitic disease of people living in the Volta Lake Basin. It is the disease most likely to increase in severity in the future, and it is the major health hazard in all of Volta Lake (VLRP, 1972). Urinary schistosomiasis (caused by the flatworm, *Schistosoma haematobium*) is by far the most common form of the disease in Ghana, with only a few areas outside the Lake basin endemic for intestinal schistosomiasis (caused by *Schistosoma mansoni*). The total number of schistosome-infested people in Ghana has been estimated at about two million. Currently, there are about 140,000 infested people in more or less isolated foci in the 1,000 villages around Volta Lake, particularly on the western side (C. K. Jones, pers. comm.). Prevalence rates commonly reach 75 percent in villages on or very near the lake. The most important intermediate host snail for *S. haematobium* in the lake is *Bulinus truncatus rohlfsi*; another intermediate host is *B. globosus*. The intermediate host for *S. mansoni* is *Biomphalaria pfeifferi*. Aquatic weeds and host snails are continually invading Bilharzia-free parts of the lake, and the disease is expected to follow in their wake.

Detailed Comments on Schistosomiasis

Present control methods.--Attempts to control schistosomiasis and research on transmission of the disease in Ghana are being carried out mainly by the Volta River Authority, Volta Lake Research Project, Ghana Ministry of Health, Institute of Aquatic Biology, and the World Health Organization. Schistosomiasis in the Volta Lake area is being attacked by the following means: (1) mechanical clearing of weeds in drawdown areas and in shallow water to reduce the extent of highly favorable habitats for host snails; (2) sanitation, e.g., providing privies in villages near the lake to reduce infection of the snail intermediate hosts; (3) providing wells and/or piped water supply to villages to reduce contact between people and water; (4) treatment of people with antihelminthic drugs; and (5) health education. No molluscicides are being used in Volta Lake. Resettlement of villages a few miles from the lake shore has had a definite effect in reducing contact between people and infested water, but the development of fishing villages on the lake is leading to increased transmission.

The magnitude of the lake (4,500-mile shoreline; 3,275 square-mile surface) and limitation of monetary and other resources prevent the application of any of these control measures throughout the entire area of the lake. Just as it is not possible at this time to apply the present control methods over the entire lake area, it is not possible to apply such control methods in all endemic regions of schistosomiasis outside the

lake area. Movement of infected persons from other endemic areas (such as the lower Volta fishing areas) to the lake and vice versa has a profound effect on disease transmission. Not only is transmission being maintained in certain areas this way, but new endemic foci are being created. Also, as a result of this movement some persons may acquire more than one strain of urinary schistosomiasis, i.e., the strain for which *Bulinus truncatus rohlfsi* serves as the intermediate host and the strain for which *B. globosus* is the host snail.

Rationale for use of biological methods of control.--Considering the seriousness of schistosomiasis and the fact that current methods, applied individually or collectively, have not been successful at the level to which they have been used, it is reasonable to consider supplemental methods of schistosomiasis control. One group of methods that may prove effective consists of various biological control techniques. Although biological control has been outstandingly effective in controlling certain agricultural pests, it has been widely applied in only very limited ways to vectors or intermediate hosts of parasitic diseases. Basic information on natural enemies of disease organisms and their hosts or vectors has only recently accumulated to the point where some promise of their application in control is apparent, and other bio-control techniques, such as genetic manipulation, have only recently been developed. The major criterion of success of a bio-control agent or technique in agriculture, i.e., reduction of the pest

population to a level that is economically tolerable, may be somewhat easier to achieve than the major criterion in control of a disease vector or host, i.e., reduction of the population of the target organism to a level where disease transmission is halted or reduced significantly. We do not know what such target population levels may be, but in regard to schistosomiasis and snail populations they would appear to be rather low. Schistosome host snails are hermaphroditic, self-fertilize, and have been observed to reproduce rather rapidly at low population densities. However, natural enemies have been used on biological controls of insect pests which have even greater intrinsic rates of population increase than do snails.

Possible objections to biological control.--Objections to biological control that are sometimes heard require clarification. The possible harmful effects of biological control, particularly the introduction of exotic species into new areas, is a legitimate consideration. The field of biological control has had a rapid development over the past 10 to 15 years, and the period of pioneering attempts is past. One needs to look at the record of purposeful introductions to assess the risk involved. For example, of 420 natural enemies introduced into the U.S.A. by the U.S. Department of Agriculture between 1884 and 1970, over 200 are effective control agents, but not one has itself become a pest (Sailer, 1972). Determination of host-prey preference is a routine part of pre-release studies in modern biological control. Suppositions that major behavioral

features of introduced species will change are biologically unsound.

Requirements for the development of biological control programs.--It is difficult to estimate the cost of developing programs of biological control. Whereas some techniques have no or low maintenance costs after introduction (e.g., introduction of exotic natural enemies), some methods may be as costly as non-biological techniques now being used. In any case, it seems realistic to assume that a considerable base of fundamental biological data will be required, and in many tropical regions where such data have not been obtained, a considerable expenditure will be required.

Major Possibilities for Biological Control of Schistosomiasis, with Reference to Ghana and Volta Lake

Possibilities for biological control of schistosomiasis are not limited to control of the snail intermediate hosts; biological control can also be attempted against the cercariae, intra-molluscan stages, and miracidia. The possibilities discussed below show special promise of success, and further research in these areas should be especially encouraged. The subject has been reviewed most recently by Ferguson and Ruiz-Tibén (1971), and Berg (1973).

Natural Enemies of Intermediate
Host Snails:

There are some laboratory and field data which indicate that, in addition to the groups mentioned below, certain other micro-organisms, insects and vertebrates may be useful as biological control agents. Practically all major groups of animals include natural enemies of gastropods. The following list includes only those natural enemies for which enough information has been obtained to make a reasonable assessment of their possible efficacy.

Predaceous and parasitoid insects.--Of the several groups of flies having larvae that feed only on snails, the family Sciomyzidae has the greatest potential. There are about 600 species of Sciomyzidae known from all parts of the world, and about 200 have been studied biologically. These 200 differ greatly in their choice of food snail, preferred microhabitat, seasonal activity, and other biological features. This diversity of biological attributes provides a rich base for selection of species adapted to different situations. Introduction of Sciomyzidae into Hawaii beginning in 1957, for biological control of the host snail of cattle fascioliasis, has shown that these flies can be mass-reared and released, that they can disperse widely from release points, and that they can successfully establish themselves in new areas. However, there are no quantitative field data to show the impact of the flies on the target snail populations.

Many aspects of Sciomyzidae are being studied in several laboratories, and programs for their application as biological control agents are being developed in Iran, Puerto Rico, and Brazil. Their major limitation is that most known larvae are air-breathers and are effective predators of snails at or a few millimeters beneath the water surface. The larvae are most successful in marshes, wet meadows, and at the edges of aquatic situations. They should also be successful biological control agents in sheltered microhabitats where there is a gradual seasonal drop in water level. Most semi-aquatic Sciomyzidae are not expected to thrive in highly disturbed situations, or (particularly in hot, dry regions) where a drastic seasonal decline in water level results in a broad, bare shoreline.

During a limited survey of a few habitats along the southern shore of Volta Lake, no situations were observed where sciomyzid flies can be applied. Sciomyzidae (Sepedon ruficeps) were found in a lagoon at Dove, near the west bank of the lower Volta River. Suitable habitats may exist around the lake or in other areas in Ghana, however, and further surveys should be carried out. Also, as only about a third of the world Sciomyzidae are known biologically, it is possible that further life cycle research will lead to the discovery of subsurface predators and species adapted to warm, exposed microhabitats. (For more detailed information on Sciomyzidae see Berg, 1964.)

Predaceous and competitor snails.--Two genera of aquatic snails, Marisa and Pomacea, from Central and South America include species that prey on eggs and juveniles of schistosomiasis host snails, or are voracious herbivores that compete ecologically with host snails. Considerable research and field trials with Marisa and Pomacea have been conducted in Puerto Rico, Egypt, and Brazil (Ferguson and Ruiz-Tibén, 1971). In certain situations Marisa and Pomacea may be undesirable in that they may become pests of agricultural crops and/or hosts of other parasitic diseases, particularly the rat lungworm, which causes meningoencephalitis in man. These aspects should be carefully determined in any program contemplating use of Marisa and Pomacea as biological control agents. Pierce recommended in 1968 that controlled, laboratory tests be conducted in Ghana to examine the feasibility of using Marisa cornuarietis as a control of intermediate host snails in Volta Lake, but this was overruled by the VLRP Hydro-Biology Advisory Sub-Committee on the grounds that the snail might escape and become a pest of rice.

A North American snail, Helisoma druryi, competes ecologically with schistosomiasis host snails and field trials are being planned in Tanzania (Berg, 1973).

Predaceous fish.--Some Cichlidae fish have been suggested as biological control agents in Africa (Bard and Mvogo, 1963; Mvogo and Bard, 1964). A puffer fish (Tetraodon sp.) that lives in Ceratophyllum beds in Volta Lake apparently is a natural

control agent and preys actively on Bulinus snails (Pierce, 1971). Pierce suggested that this fish be protected and possibly encouraged. Reynolds (pers. comm.) informs that young Lates, Alestes baremose, Physailia, and Synodontis spp. attack Bulinus snails, although to only a slight extent. Further research on snail predation by these and other fishes is desirable.

Waterfowl.--Ducks and geese confined on ponds can eradicate snail populations, but their effects in more extensive areas is unknown. Snail control field workers on Volta Lake have noted a correlation between low populations of snails and presence of domestic ducks around certain villages on the lake. Wild ducks have been introduced in certain endemic areas, e.g., Venezuela, but were not successfully established as the people were highly effective predators of the ducks. Waterfowl as biological control agents would seem to have more application in endemic areas in Ghana other than Volta Lake, but both situations warrant further study.

Genetic Manipulation of
Snail Populations:

Species of schistosome host snails include some races susceptible to infection by Schistosoma and some races that are non-susceptible. This feature has a genetic basis, and Hubendick (1958) suggested ways in which races of non-susceptible snails might be useful when introduced into habitats of susceptible snails. If non-susceptible races can be bred that are more

vigorous and develop more quickly than susceptible races, they should be able to outcompete the susceptible races. Furthermore, non-susceptible snails will hybridize with susceptible snails and the offspring will have lower susceptibilities than the susceptible parents. Considerable research on this subject is being conducted by Dr. C. S. Richards, U.S. National Institute of Health. Related research on snail genetics is being carried out by Dr. W. Coker at the University of Ghana, Legon. Field work with natural populations is being developed in Brazil by Dr. H. C. Barnett at Bahia, and by Dr. Richards and Prof. F. S. Barbosa at Brasilia.

Natural Enemies of Schistosome Cercariae and Miracidia:

There are several natural enemies of these stages of the schistosomiasis cycle, but they are not yet being researched in Ghana. Several invertebrates, including oligochaete worms, mosquitoes, and Hydrozoa, are known to kill schistosome cercariae and miracidia. The detailed ecology of these organisms is unknown, and nothing is known of their impact on transmission of schistosomiasis. Guppies (*Lebistes reticulatus*) are known to feed voraciously on cercariae, and quantitative laboratory and field studies have shown that they have a significant effect on disease transmission rate (Pellegrino *et al.*, 1966; Knight *et al.*, 1970).

Control of Intramolluscan
Stages of Schistosomes:

Antagonistic trematode larvae.--Trematode larvae that do not cause human disease may be used against schistosome larvae. Various non-disease producing trematode larvae (families Echinostomatidae and Strigeidae) have asexually reproducing stages that also live in snail intermediate hosts of schistosomes. Both schistosome and non-schistosome cercariae may enter a snail, but the subsequent redial stages are antagonistic. One species becomes dominant, the other, subordinate. Frequently, rediae of one species will prey on rediae of the second species. Indirect antagonism between sporocyst stages of two species of trematodes living in one snail causes a retardation of development of the subordinate species. The mechanism of indirect antagonism is not clearly known; it may be caused by competition for food, toxic products of metabolism, or formation of immune substances by the host.

Theoretically, a dominant non-disease causing trematode may be used to control a medically important, subordinate trematode by reducing the number of subordinate trematodes through direct or indirect antagonism, or by making the host snail refractory to further infection by schistosomes. Also, non-disease producing trematodes may be used to shorten the life of snails, or to reduce their fecundity by parasitic castration. Field trials of schistosome trematodes whose rediae prey on schistosome intramolluscan stages have been conducted in Malaysia (Lie et al., 1970) and other tests are underway in Ethiopia.

Relationship of Aquatic Weeds and Schistosomiasis

The distribution of schistosomiasis host snails is closely correlated with that of the aquatic weeds which provide the snails with food, shelter, and oviposition and development sites. Although aquatic weeds are not a major problem in Volta Lake in the sense that they do not at all interfere with production of electricity and interfere to only a limited extent with fishing and transportation (Opoku, pers. comm.), there is in fact a well-developed flora. Extensive weed control along the 4,500-mile shoreline of Volta Lake is obviously impractical with present methods and from the point of view of fish production and certain other aspects, it is also undesirable. The most significant negative aspect of aquatic weeds in Volta Lake is their importance as substrates for bilharzia snails.

Unfortunately, comments such as that on p. 91 of The Green Revolution (Johnson, 1971), that the ecology of Volta Lake is changing in a direction unfavorable to snails, were premature and based on lower snail populations accompanying the decrease of sudd during 1967-68. Although the importance of *Pistia*, a major component of sudd, has decreased greatly, the presently dominant submerged weed *Ceratophyllum* apparently is by far the substrate most preferred by bilharzia snails (Odei, 1973).

The method of weed control that appears most useful in loci of bilharziasis consists of mechanical clearance on the drawdown area in front of fishing villages, with subsequent

herbicide treatment (Pierce and Opoku, 1971). This method eliminates the inshore weeds and the snails that they harbor. It likely has an effect on bilharziasis transmission, as most transmission takes place in a zone close to the shore, but its significance has not been determined. However, in many areas Ceratophyllum beds extend up to 20 meters from the shore and to a depth of 9 meters. Although this rate is as yet unknown, it appears to be in the order of one-and-a-half to two years (Odei, pers. comm.).

There is no area-wide weed control program in progress, and no biological control is being carried out, although this approach has been considered. Present efforts are directed to surveillance of the weed fauna and research (Opoku, pers. comm.). The limited use of agricultural fertilizers in drawdown areas apparently does not now have a significant effect on the growth of aquatic weeds, but direct fertilization of the lake probably would stimulate their growth.

A chrysomelid (Atlica nigrata or senegalensis) beetle has been found to be a natural enemy of the weed Ludwigia leptocarpa growing on the exposed shore (Pierce, 1971), and the biology of this species is being studied (Odei, pers. comm.). Manatees (Trichechus sp.) consume great quantities of weeds; they occurred well up the Volta River before the lake was formed, but none has been seen in the lake since 1966. Pierce (1971) stated that it is highly unlikely that any large aquatic animal would be suitable for controlling aquatic weeds at Volta Lake.

He judged that they would certainly be destroyed by the fishermen for no other reason than to stop the animals from damaging their gear, which is commonly set in the shallow, weed-infested areas of the lake.

General Conclusions and Recommendations

1) Several known or potential biological control agents of the snail intermediate host of schistosomiasis on Volta Lake seem worthy of research: the puffer fish (*Tetraodon* sp.) and other predaceous fish, and waterfowl (ducks and geese). Initially, relatively simple, inexpensive field tests should be carried out to determine their efficacy in snail predation.

2) The potential values of other biological control agents are largely hypothetical. Included are predaceous and parasitoid insects (e.g., sciomyzid flies), genetic manipulation of snails, natural enemies of cercariae and miracidia forms, and antagonistic trematode larvae. For these agents, basic biological and ecological research is required before application possibilities can be envisaged.

3) Biological methods of control in man-made lakes can best be developed in a more or less stable physical environment. Environmental stability is particularly important in regard to aquatic plants, which usually provide the most important substrates for snail hosts of schistosomiasis. Since the aquatic plants of Volta Lake have attained relative stability

in succession, biological control methods can be considered.

4) Most regions where man-made lakes are or might be developed are in fact areas where there is very little basic information on the flora and fauna. Knowledge of the relationships between the candidate biological control agent(s), the target organism, and other members of the ecosystem is critical for successful application of biological control. Also, surveys of the diversity of the plants and animals and basic taxonomic studies are fundamental needs. The diversity of the Ghanaian flora and fauna, the relative ease of transportation within the country, the relatively broad base of scientific knowledge in Ghana compared to other areas, the sophisticated and extensive development of biological science in Ghana, and other relevant factors indicate that research on biological control in Ghana is feasible and could produce significant results.

REFERENCES CITED

Abhyankar, N. G. 1964. The multi-purpose aspect of the Volta River Project. Econ. Bull. Ghana, 8(1):27-33.

Adiase, M. K. 1969. A preliminary report on the food of fish in the Volta Lake. In L. E. Obeng (ed.), Man-Made Lakes, The Accra Symposium. Ghana Univ. Press, Accra, pp. 235-237.

Addo-Ashong, F. W. 1969. Effect of flooding on decomposition of wood. In L. E. Obeng (ed.), Man-Made Lakes, The Accra Symposium. Ghana Univ. Press, Accra, pp. 292-297.

Amatekpar, J. 1970. Some investigations on soils, agricultural land-use, insect pests, and plant diseases, in the draw-down area of Volta Lake. Volta Basin Research Project, Tech. Report x36. University of Ghana, Legon.

Amissah, A.N.D. 1969. Some possible climatic changes that may be caused by Volta Lake. In L. E. Obeng (ed.), Man-made Lakes, The Accra Symposium. Ghana Univ. Press, Accra, pp. 73-82.

Annan, C. K. 1973. Long-term multi-purpose water demand of the northern and upper regions of Ghana. Ghana Water and Sewerage Corporation, Unpublished Report.

Annan-Yorke, R., and J. E. Cudjoe. 1971. Geology of the Voltaian Basin. Ghana Geol. Survey Dept., Spec. Bull., 29 pp.

Anonymous, 1954. Nile project and its effects in the Anglo-Egyptian Sudan. Report of the Jonglei Investigation Team, Sudan Government, Khartoum.

_____. 1965. Snail control in the prevention of Bilharziasis. WHO, Geneva, 255 pp.

_____. 1966. Mulching with water hyacinth (Eichhornia crassipes): Two and a bud 13:31 (Abstract). In Little (ed.), Handbook of Utilization of Aquatic Plants. FAO, Rome, 1968, p. 17.

_____. 1971a. Volta Lake research. Interim Report, UNDPFI. SF/GHA-10. FAO, Rome.

_____. 1971b. Volta River Authority, 10th Annual Report. VRA, Accra, Ghana.

_____. 1972. Technical reports and working paper of the lake-wide survey of Lake Nasser and Lake Nubia. Aswan Reg. Planning and Lake Nasser Development Project Center, Aswan.

Attionu, R. 1970. Eco-physiological studies on Pistia stratiotes L. with special reference to its occurrence on the Volta Lake in Ghana. M.Sc. Thesis. University of Ghana, Legon.

Aziz, M. A. 1973. Preliminary annotated bibliography of the hydrobiology of Lake Volta. Smithsonian Institution, Office of Environmental Sciences.

Bannerman, R. R. 1972a. Groundwater resources of Ghana, development and management. GWSC/WHO Seminar on water for health. Accra. Mimeo., 6 pp.

_____. 1972b. Problems of groundwater development in the Voltaian sedimentary basin of Ghana. West African Sci. Assoc. 8th Ann. Conf., Legon. Mimeo., 12 pp.

Bannerman, R. R., K. Atobrah, and P. H. Neequaye-Tetteh. 1972. A map of groundwater availability in Ghana. West African Sci. Assoc. 8th Ann. Conf., Legon. Mimeo., 7 pp.

Bard, J., and L. Mvogo. 1963. Note d'information sur l'Astatoreochromis alluaudi poisson molluscophage utilisable dans la prophylaxie de la bilharziose. Bull. Soc. Pathol. Expt., 56:119-120.

Barning, K., and J. Banson. 1969. Possible sedimentation and seismic effects on Volta Lake. In L. E. Obeng (ed.), Man-Made Lakes, The Accra Symposium. Ghana Univ. Press, Accra, pp. 83-90.

Barraclough, W. E., and D. G. Robinson. 1972. The fertilization of Great Central Lake. III. Effect on sockeye salmon. Fish. Bull., 70:[illegible]-48.

Bazigos, G. P. 1971. Yield indices in inland fisheries with special reference to Volta Lake. UNDP/VLRP Statistical Studies F 10. SF/GHA/10.

Beeton, A. M. S. Smith, and F. Hooper. 1967. The physical limnology of Saginaw Bay, Lake Huron. Great Lakes Fish. Comm. Tech. Rept. no. 12, 56 pp.

Berg, C. O. 1964. Snail control in trematode diseases; the possible value of sciomyzid larvae, snail-killing Diptera. Advances in Parasitol., Vol. 2. Academic Press, London and New York.

_____. 1973. Biological control of snail-borne diseases, a review. Expt. Parasitol., 33:318-330.

Bird, C. St. J. 1949. Volta River Scheme: Gold Coast colony. A report to West African Aluminium, Ltd., 3 vols.

Biswas, S. 1970. Changes in the phytoplankton of the developing Volta Lake. Ghana J. Sci., 10:85-95.

_____. MS (nd). Limnology of Volta Lake, 1964-72 (Final Report). Typewritten. Volta Basin Research Project, Univ. Ghana, 84 pp.

Boughey, A. 1963. The explosive development of a floating weed vegetation on Lake Kariba. Adansonia, 3:49-61.

Bowmaker, A. 1970. A prospect of Lake Kariba. Optima, 20: 68-74.

Boyd, C. 1970. Chemical analysis of some vascular aquatic plants. Arch. Hydrobiol., 67:78-85.

Bradley, W. H. 1966. Tropical lakes, copropel, and oil shale. Geol. Soc. America Bull., 77:1333-1338.

Bretschko, G. 1971. Instructions for calculating stability with special reference to Lake Volta. Report to VLRP.

_____. 1972. Progress report to VLRP, April-July, 1972.

Clark, J. G. D. 1952. Prehistoric Europe: the economic basis. Methuen, London, ix + 349 pp.

Czernin-Chudenitz, C. 1971. Recent limnological status of Volta Lake, Ghana. Paper presented at the Man-Made Lakes Symposium, Knoxville, Tenn., 1971.

Denton, J. 1965. Relationships between the chemical composition of aquatic plants and water quantity. M.S. Thesis. Auburn Univ., Alabama.

Denyoh, F.M.K. 1969. Changes in fish population and gear selectivity in the Volta Lake. In L. E. Obeng (ed.), Man-Made Lakes, The Accra Symposium. Ghana Univ. Press, Accra, pp. 206-210.

El Din el Zarka, S. 1974. Kainji Lake (a case history). Man-Made Lakes Symposium. Knoxville, Tenn., 1971 (in press).

Entz, B.A.G. 1969. Limnological conditions in Volta Lake, the greatest man-made lake of Africa. Nature and Resources Bull. Int. Hydrol. Decade, UNESCO, 5(4): 9-16.

_____. 1969. Observations on limnological conditions in the Volta Lake. In L. E. Obeng (ed.), Man-Made Lakes, The Accra Symposium. Ghana Univ. Press, Accra, pp. 110-115.

Evans, W. A. 1969. Is Volta Lake being overfished or underfished? VLRP, Akosombo, December.

Ewer, D. W. 1966. Biological investigations on the Volta Lake May, 1964 to May, 1965. In R. H. Lowe-McConnell (ed.), Man-Made Lakes, Inst. of Biology Symposia. No. 15, Academic Press, London, pp. 21-31.

FAO. 1971. Volta Lake Research, Ghana. Physico-chemical conditions of Lake Volta, Ghana, based on the work of C. W. Czernin-Chudenitz. FI:SF/GHA 10, Tech. Rep. 1.

Faroq, M. 1967. Progress in bilharziasis control: th situation in Egypt. WHO Chronicle, 21:175-184.

Ferguson, F. F., and E. Ruiz-Tibén. 1971. Review of biological control methods for schistosome-bearing snails. Eth. Med., 9:95-104.

Garrels, R. M., and F. T. Mackenzie. 1971. Evolution of sedimentary rocks. Norton, New York, 397 pp.

Gaudet, J. 1973. The normal role of vegetation in water. In Mitchell (ed.), A Review of Improved Means of Monitoring and Controlling Aquatic Vegetation. UNESCO (IHD/IBP) (in press).

Gay, P. 1958. Eichhornia crassipes in the Nile of the Sudan. Nature, 182:538.

Halcrow, Sir William, and Partners. 1951. Report on development of the River Volta Basin. London.

_____. 1955. Material for impervious core of Ajena Dam. First report on construction of an experimental clay bank. November.

_____. 1956. Volta River Project: Engineering report to the preparatory commission, vol. 2, pp. 220-222.

Hall, J. 1970. Observations on the vegetation of the Lake Volta drawdown area. Volta Basin Research Project, Tech. Report x 35. University of Ghana, Legon.

Hall, J., and W. Pople. 1968. Recent vegetational changes in the lower Volta River. Ghana J. Sci., 8:24-29.

Hall, D. J., W. E. Cooper, and E. E. Werner. 1970. An experimental approach to production dynamics and structure of freshwater animal communities. Limnol. Oceanogr., 15:839-928.

Hall, J. B., P. Pierce, and G. Lawson. 1971. Common plants of the Volta Lake. Botany Dept., University of Ghana.

Hall, J. B., E. Laing, M. Hossain, and G. Lawson. 1969. Observations on aquatic weeds in the Volta Basin. In L. E. Obeng (ed.), Man-Made Lakes, The Accra Symposium. Ghana Univ. Press, Accra, pp. 331-336.

Hayes, F. R., J. A. McCarter, M. L. Cameron, and D. A. Livingstone. 1952. On the kinetics of phosphorus exchange in lakes. J. Ecology, 40:202-216.

Hestand, R., and C. Carter. 1973. The invasion and establishment of aquatic plants in Lake Ocklawaha during a drawdown. Hyacinth Control Journal, 12 (in press).

Hilton, T. E. 1961. The fisheries of the Volta System of Ghana. Oriental Geographer, 5:21-34.

Hirst, T. 1938. Geology of the Tarkwa goldfield. Gold Coast Geol. Survey Bull., 10.

_____. 1962. Geology of the Konongo Gold Field. Gold Coast Geol. Survey Bull., 14: 23 pp.

Hubendick, B. 1958. A possible method of schistosome-vector control by competition between resistant and susceptible strains. Bull. WHO, 18:1113-1116.

Hunter and Mitchell. 1968. Citation pending.

Hutchinson, G. E. 1950. Survey of contemporary knowledge of biogeochemistry. III. The biogeochemistry of vertebrate excretion. Amer. Mus. Nat. Hist. Bull., 96:554.

Ita, E. O. 1972. Approaches to the evaluation and management of the fish stock in Kainji Lake, Nigeria. FAO, CIFA, Symp. on evaluation of fishery resources, Fort-Lamy.

Jenkins, D. W. 1964. Pathogens, parasites and predators of medically important arthropods. Bull. WHO, 30 (Suppl.).

Johnson, S. 1972. The Green Revolution. Harper, New York.

Junner, N. R. 1942. The Accra earthquake of 22nd June, 1939. Gold Coast Geol. Survey Bull., 13, 67 pp.

Junner, N. R., and T. Hirst. 1946. Geology and hydrology of Voltaian Basin. Gold Coast Geol. Survey Mem. 8.

Kaiser, Henry J. Company. 1959. Reassessment report on the Volta River Project for the Government of Ghana. Kaiser Engineers, Oakland.

_____. Volta River Project: electrical power system study and analysis. 3 Vols. Report no. KEI-64-11-R. Kaiser Engineers, Oakland.

Kilham, Peter. 1972. Biogeochemistry of African lakes and rivers. Doctoral dissertation, Duke University, xii + 199 pp.

Klima, E. F., and D. A. Wickham. 1971. Attraction of coastal pelagic fishes with artificial structures. Trans. Amer. Fish. Soc., 100(1):86-99.

Knight, W. B., L. W. Ritchie, F. Liard, and J. Chiriboga. 1970. Cercariophagic activity of guppy fish (Lebistes reticulatus) detected by cercariae labeled with radioselenium (75_{se}). Am. J. Trop. Med. and Hyg., 19(4): 620-625.

Krishnamurthy, K. 1964. The Volta River Akosombo dam. International Commission on Irrigation and Drainage, Ann. Bull., pp. 98-104.

Kuzoe, F.A.S. 1970. Some observations on Simulium damnosum from southern Ghana. Ghana J. Sci., 9:35-40.

_____. 1971. Distribution of Glossina in areas peripheral to the Volta Lake. OAU/STRC Publ. 105.

Kumi, E. N. 1973. Environmental effects of the Volta River Project. Comm. International des Grands Barrages, 11th Congress, Madrid, pp. 907-921.

Lartey, G. M., and M. Smith. 1968. Water resources development in Ghana: problems and role in national development planning. Accra, Water Resources Research Unit, Ghana Acad. Sci., 1968, 80 pp.

Lawson, G. 1963. Preliminary report on the aquatic weeds in the Volta Basin. Volta Basin Research Project, Tech. Rept. x 6, University of Ghana, Legon.

_____. 1964. Control of aquatic weeds in the Volta Basin. VBRP Tech. Rep. x 1.

_____. 1967. "Sudd" formation on the Volta Lake. Bull. IFAN, Ser. A29(1):1-4.

_____. 1970. Lessons of the Volta--A new man-made lake in tropical Africa. Biol. Conservat., 2(2):90-96.

Lawson, G. W., T. Petr, S. Biswas, E.R.I. Biswas, and J. D. Reynolds. 1969. Hydrobiological work of the Volta Basin Research Project 1963-1968. Bull. de l'IFAN, Tome XXXI, Ser. A(3):965-10003.

Leonard, J. 1969. Apercu sur la vegetation; complement on chapitre I de la monographie hydrologique de Lac Tchad. Service Hydrologique, ORSTOM, Paris.

Le Brasseur, R. J., and O. D. Kennedy. 1972. The fertilization of Great Central Lake. II. Zooplankton standing stock. Fish. Bull. U.S., 70:25-36.

Lessent, P. 1966. Essai de fertilisation des étangs à la station de recherches piscicoles de Bouaké, Côte d'Ivoire. MS.

_____. 1967. Compte-rendu des essais de fertilisation des étangs réalises au cours du ler semestre, 1967. MS.

Lie, J. K., K. H. Hoa, and O. C. Kong. 1970. A field trial to test the possible control of Schistosoma spindale by means of interspecific trematode antagonism. S. East Asian J. Trop. Med., Pub. Health, 1(1):19-28.

Lind, E., and S. Visser. 1962. A study of a swamp at the north end of Lake Victoria. J. Ecology, 50:599-613.

Loiselle, P. V. 1970. A study of the fish populations of the littoral zone of Lake Volta, Ghana: preliminary report. VLRP, December 1970.

_____. 1971. Checklist of Volta Lake fishes. MS.

_____. 1972. Preliminary survey of inshore habitats in the Volta Lake. UNDP FI:PP/GHA/67/510/2. FAO, Rome.

McJunkin, F. 1970. Engineering measures for control of schistosomiasis. Rep. Off. Health, Bur. Tech. Asst., AID/csd-2487. Washington, D.C.

Mitchell, D. 1969. The ecology of vascular hydrophytes on Lake Kariba. Hydrobiol., 34:448-464.

Mitchell, J. 1960. Limestones of Ghana. Ghana Geol. Survey Bull., 23, 2 vols.

Modlin, R., and A. M. Beeton. 1970. Dispersal of Fox River water in Green Bay, Lake Michigan. Proc. 13th Conf. Great Lakes Res., Int. Assoc. Great Lakes Res., pp. 15-46.

Mohring, H., and J. H. Boyd. 1971. Analyzing "externalities": "direct interaction" versus "asset utilization" frameworks. Economica, 38:347-361.

Mvogo, K., and J. Bard. 1964. Seconde note d'information sur l'Astatoreochromis alluaudi, poisson malacophage utilisable dans la prophylaxie de la bilharziose. Bull. Soc. Pathol. Expt., 57:21-23.

Nathan Consortium. 1970. Water resources development in Ghana. Interim Report B, Occurrence of groundwater; Interim Report I, Sediment sampling program.

Nelson, P. R., and W. T. Edmondson. 1955. Limnological effects of fertilizing Bare Lake, Alaska. U.S. Fish Wildl. Serv., Fish. Bull., 56:414-436.

Odei, M. 1973. Observations on some weeds of malacological importance in the Volta Lake. Bull. de l'IFAN, 35 (in press).

Okorie, O. O. 1972. Some major unsolved aspects of the dynamics of African fisheries as related to questions of national development and management. FAO/CIFA Symp., Fort-Lamy, November-December.

Opoku, A. 1971. Quarterly Progress Report, VLRP, Akosombo, Ghana (July-December).

_____. 1973. Quarterly Progress Report, VLRP, Akosombo, Ghana (January-March).

Paperna, I. 1969. Aquatic weeds, snails and transmission of bilharzia in the new man-made Volta Lake in Ghana. Bull. de l'IFAN, 31:487-499.

Parsons, T. R., K. Stephens, and M. Takahashi. 1972. The fertilization of Great Central Lake. I. Effect of primary production. Fish. Bull. U.S., 70:13-23.

Pellegrino, J. M. de Maria, and M. F. de Moura. 1966. Observations on the predatory activity of Lebistes reticulatus (Peters, 1859) on cercariae of Schistosoma mansoni. Am. J. Trop. Med. Hyg., 15(3):337-341.

Petr, T. 1967a. Fish population changes in the Volta Lake in Ghana during its first sixteen months. Hydrobiologia, 30:193-220.

_____. 1967b. Food preferences of the commercial fishes of the Volta Lake. VBRP Tech. Rep. x 22.

_____. 1968. Distribution, abundance and food of commercial fish in the Black Volta and the Volta man-made lake in Ghana during its first period of filling (1964-1966). I. Mormyridae. Hydrobiologia, 32:417-448.

_____. 1971. Lake Volta--A progress report. New Scientist, 49(736):178-180.

Pierce, P. 1968. Technical field reports, USAID Volta Lake Technical Assistance Project (641-11-190-028), USAID, Accra.

_____. 1971. Aquatic weed development, impact and control at Volta Lake, 1967-71. USAID Volta Lake Technical Assistance Project 641/11/190/028.

Pierce, P., and A. Opoku. 1971. Summary of aquatic weed survey and control data for Volta Lake during 1969. Hyacinth Control Journal, 9:49-56.

Pople, W., and M. A. Mensah. 1971. Evaporation as the upwelling mechanism in Ghanaian coastal waters. Nat. Phys. Sci., 234:18-20.

Proszynska, M. 1967. A quantitative study of the Cladocera and Copepoda in the Afram confluence area of the Volta Lake. Typewritten. Report to VLRP.

_____. 1969. A preliminary report on the quantitative study of the Cladocera and Copepoda in the Volta Lake 1964-1965. In L. E. Obeng (ed.), Man-Made Lakes, The Accra Symposium. Univ. Ghana Press, Accra, pp. 127-132.

Rajagopal, P. K. 1969. Preliminary observations on the vertical distribution of plankton in different areas of the Volta Lake. In L. E. Obeng (ed.), Man-Made Lakes, The Accra Symposium. Univ. Ghana Press, Accra, pp. 123-126.

Ram, J. 1968. Eyes on the Volta Lake. New Sci., 12th Sept.:540-541.

Regier, H. A. 1971. Evaluation of fisheries resources in African inland waters. Report Sem. on Fisheries Resource Assessment, Bujumbura, 1-7 June, 1971.

Reynolds, J. D. 1967. Notes on juveniles of commercial fishes attracted to light on the Volta Lake, 1966-1967. VBRP Tech. Rep. x 21.

_____. 1968. Biological studies of the small pelagic fishes of the New Volta Lake, Ghana. MSc. Thesis. Dublin.

_____. 1969. The biology of the Clupeids in the New Volta Lake. In L. E. Obeng (ed.), Man-Made Lakes, The Accra Symposium. Ghana Univ. Press, Accra, pp. 195-203.

_____. 1970. Biology of the small pelagic fishes in the new Volta Lake in Ghana. Part I. The lake and the fish: feeding habits. Hydrobiologia, 35:568-603.

_____. 1971. Biology of the small pelagic fishes in the new Volta Lake in Ghana. Part II. Schooling and migrations. Hydrobiologia, 38:79-91.

_____. 1973a. Biology and fisheries potential of four species of Alestes (Pisces: Characinidae). Rev. Zool. Bot. Afr. (in press).

_____. 1973b. Biology of the small pelagic fishes in the new Volta Lake in Ghana. Part III. Reproduction. Hydrobiologia (in press).

Richardson, G. F. 1970. Lake drawdown area. An appraisal of crop results from November 1968 to July 1970. VLRP report.

Richardson, L. 1973. Water level manipulation: a tool for aquatic weed control. Hyacinth Control Journal, 12 (in press).

Reimer, D., and W. Welker. 1973. Experiments on the control of spatterdock and fragrant waterlily with glyphosphate. Hyacinth Control Journal, 12 (in press).

Ryder, R. A. 1965. A method for estimating the potential fish production of north-temperate lakes. Trans. Amer. Fish. Soc., 94:214-218.

Sailer, R. I. 1972. A look at USDA's biological control of insect pests: 1888 to present. Agric. Sci. Rev., 10: 15-27.

Stumm, W., and J. J. Morgan. 1970. Aquatic chemistry--an introduction emphasizing chemical equilibria in natural waters. Wiley, New York, 583 pp.

Tevendale, W. B. 1957. Geology of the Volta River Project. Ghana Geol. Survey Bull., 20, 119 pp.

Thompson, K., and J. Gaudet. 1973. A review of papyrus and its role in tropical swamps. Archiv für Hydrobiologie (in press).

Vanderpuye, J. 1971. Assessment of clupeids. VLRP Working Report.

_____. 1972. Fishery resource development and monitoring in the development and control of fisheries in the Volta Lake. VLRP, April 1972.

Vanderpuye, J., and P. Ocansey. 1972. A preliminary study of the biology of Lates niloticus in Volta Lake. VLRP Report.

Viner, A. B. 1969a. Observation of the hydrobiology of the Volta Lake, April 1965-April 1966. In L. E. Obeng (ed.), Man-Made Lakes, The Accra Symposium, Ghana Univ. Press, Accra, pp. 133-143.

_____. 1969b. The limnochemical work carried out at Lake George between April 1967 and February 1968. In UNESCO 1969 Report Regional Mtg. Hydrobiol., Makerere Univ.

_____. 1970a. Hydrobiology of Lake Volta. I. Stratification and circulation of water. Hydrobiologia, 35:209-229.

_____. 1970b. Hydrobiology of Lake Volta. II. Some observations on biological features associated with the morphology and water stratification. Hydrobiologia, 35: 230-248.

Volta Basin Research Project. 1964. Clearance of the vegetation in the Volta by burning. Volta Basin Research Project Tech. Rept. no. 2, University of Ghana.

VLRP. 1971. Quarterly progress report, October-December 1970. Volta Lake Research Project, Volta River Authority, Accra.

_____. 1971. Volta Lake Research, Ghana. Interim Report, 1971. F1 SF/GHA 10.

_____. 1972. Quartery progress report, October-December, 1972. Volta Lake Research Project, Volta River Authority, Accra.

_____. 1973. Quarterly progress report, January-March, 1973. Volta Lake Research Project, Volta River Authority, Accra.

Volta River Authority. 1971. Tenth Annual Report, 54 pp.

Volta River Project Preparatory Commission. 1956. The Volta River Project. London, H.M.S.O., 1956, 3 vols.

_____. 1956. Relationship of the Volta River Project to agriculture, forests and fisheries. In the Commission's Volta River Project, vol. 2, 1956, pp. 211-229.

Water Resources Research Unit, CSIR. 1971. Fourth Annual Report, 29 pp.

Welcomme, R. L. 1972. The inland waters of Africa. CIFA/T1, FAO, Rome, 1972, CIFA Tech. Rept. i.

Whitehead, V. 1969. Investigations into the food habits of some juvenile fish in the Volta Lake during the period October 1967 to March 1969, with some notes on distribution and abundance. VBRP Tech. Rept. x 30.

Wild, H. 1961. Harmful aquatic plants in Africa and Madagascar. CCTA/CSA Publ. no. 73, Salisbury.

Wilson, L. 1941. The larger aquatic vegetation of Trout Lake, Vilas County, Wisconsin. Trans. Wisc. Acad. Sci. Arts and Letters, 33:135-146.

World Bank. 1971. Water supply and sewerage. Sector Working Paper, World Bank, Washington, D.C. 15 pp.

Wright, W. 1968. Schistosomiasis as a world problem. Bull. N.Y. Acad. Med., 44:301-312.

APPENDIX 1

Notes on Calculations of Nutrients Trapped by Water Weeds

Area Covered (Estimate)

In order to calculate the total nutrient trapped, it was necessary to estimate the percentage of shoreline covered along the lake shore. This estimate was based on visual reports of several workers who have frequented many areas on the lake during the last few years. Since the shoreline is approximately 5,000 km, it is then possible to calculate an estimate of the length of shoreline occupied by each category of aquatic weed, i.e., submerged (A), floating (B), and emergent (C), where A = 13% or 650 x 10^3 m; B = 10% or 500 x 10^3 m; and C = 100% or 5,000 x 10^3 m. The average distance from shore in each category was estimated to be: A_1 = 20 m, B_1 = 5 m, and C_1 = 100 m. Thus, the area covered (estimate) for each category would be:

$$A \times A_1 = 13 \times 10^6 m^2,$$

$$B \times B_1 = 2.5 \times 10^6 m^2,$$

$$C \times C_1 = 500 \times 10^6 m^2.$$

Total Trapped

Several factors were already known or estimated as closely as possible, such as:

a. Area covered: A_1, B_1, and C_1 above.

b. Biomass of each category: A_2, B_2, and C_2 (see Table 13). Thus total biomass, i.e., dry weight for each category would be: $A_3 = 87 \times 10^5$ kg; $B_3 = 12 \times 10^5$ kg; and $C_3 = 3{,}800 \times 10^5$ kg.

c. Percent of each nutrient on a dry weight basis: A_4, B_4, and C_4 (shown in Table 13). Thus for each nutrient, $A_3 \times A_4 + B_3 \times B_4 + C_3 \times C_4$ = total trapped.

APPENDIX 2

Field Observations Made on the Volta Lake By Dr. J. D. Reynolds During May, 1973

Dr. Reynolds made two short lake trips, the first a familiarization trip during which he traveled about one km along the Ajena inlet and examined dead wood at the shore. The second trip was made through the Gorge Region to the Pawmpawm Bay, where he collected and examined plankton samples, drowned wood, aquatic and drawdown vegetation, and checked catches of fish in several villages. He also traveled by lake to Yapei, during which he was able to observe the lake in its entirety, and compare it with the situation on his last trip in 1969. Dr. Reynolds was assisted by Mr. Frank Denyoh and Mr. Owereku of the VLRP during his field trips.

Substrate

At Ajena, the shallows were sandy-silty, with few rock outcrops. No benthic aufwuchs layer was seen. Shores were rocky and exposed chiefly on the east side of the Gorge and of Pawmpawm Bay. In the bay, stretches of sand 5-10 m wide were common, with sparse vegetation. Rocks and trees inshore were usually covered with filamentous algae and

aufwuchs layers 10 to 30 mm thick. The sand itself was firm and clean. This shore development was much different from anything observed up to 1969.

At Yeji, the substrate was silty with organic debris, looking similar to that seen in 1968-1969. Between Mpaha and Yapei, the uniform, firm river banks were still visible. In the uppermost reaches a dredger kept the shallow channel open; as most silt deposition will occur in this restricted area, such action will always be necessary.

Weeds

At Ajena, logs were sometimes crowned with sedges. Inshore were occasional patches of Potamogeton, a recent addition to the south of the lake (Opoku, pers. comm.) and small tufts of Ceratophyllum. On a small island in the Gorge there was a bed of partly emergent, partly floating Vossia, the only patch seen in this area. One bay only in the Pawmpawm area had tufts of Ceratophyllum rooted in sand, but no other aquatic plants were seen except for one battered Pistia plant washed up, although over one mile of shore was examined.

Weeds were little evident below Mpaha, but uplake in the White Volta arm, small floating reed patches were seen in the flooded trees, then more extensive patches fringing islands and shallows, thus allowing the Vossia etc. a firm rooting. The sudd was up to 500 m wide, extending from the banks in

the upper parts in an almost unbroken sward. With the floods and rising waters this should form a valuable fish refugium and nursery.

Periphyton

At Ajena, periphyton was 5 to 10 mm thick on boats and docks, and a very thin film was seen on *Potamogeton* leaves. The associated fauna washed from aquatic plant clippings included one mite and about 12 chironomid larvae. Wood collected in Pawmpawm Bay had a thin film of diatomaceous aufwuchs on the corrugated bark, sheltering a diverse fauna (see Table 17). The films seemed thicker, closer inshore. Dense filamentous algae clothed one inshore rock in 15 cm of water.

TABLE 17. Invertebrate Species Composition on Savannah Tree, Pawmpawm Bay (on Branch 3 cm Diameter, 60 cm in Length)

Organism	Number	Length Range (mm)
Trichopteran larva	24	1 - 10
Trichopteran pupae	1	8
Chironomid larvae	10	3 - 4
villa nymphs	1	10
Oligochaetes	2	6

Drowned Trees

At Ajena, some crumbling softwood logs and tree bases were seen at the shore, completely riddled with Povilla (ephemerid) burrows. This invertebrate's attacks seem to have almost completely removed trees of such species as Ceiba pentandra (silk-cotton). Harder wooded trees were still visible in shallows, lacking small twigs but not apparently attacked by Povilla (Petr, 1969). These savannah trees predominate throughout the lake, stretching some miles into the Pawmpawm arm. Here silk-cottons were again greatly eroded by Povilla, but still retained the trunk, and perhaps one or two branches. Many Povilla exuviae were seen on the shoreline.

Flooded trees from Kete Krachi south seemed less dense than four years ago, particularly near landings, but in the northern arm the situation looked relatively unchanged. Many trees had all branches lower than 2 m above water level and so would be covered at high water; twigs down to 2 cm diameter were retained. Above Mpaha, flooded savannah trees were still very dense. Silk-cottons in the north were few, but were much less damaged than further south, retaining small branches of perhaps 10 cm diameter in some cases. Their relatively intact state was seen particularly at Makongo and in the Pru arm.

Plankton

Samples were taken at three points offshore in the southern lake, but the net was too coarse to allow quantitative assessments. In the top 2 m of the deep water off Ajena Bay and Pawmpawm Bay, several copepods were taken, with much *Volvox* also at the latter station. In 150 cm water about 6 m offshore at Pawmpawm, no zooplankters were seen, but water was very greenish. Thus, plankters appeared patchy. No distinct water-blooms were seen, though none were expected owing to the depressed nutrient regime at this season.

Drawdown

This year the vertical extent of the drawdown seems to have been about 3.0 to 3.5 m; maximum lake level has not been reached for several years (VRA annual reports). In Ajena Bay, it was estimated that about 50 to 80 percent of the drawdown was cultivated, planted chiefly with maize and cassava. The rest was largely barren up to the high grass (probably *Sorghastrum*) level. In the Gorge the drawdown was 50 percent covered with grasses, but on the sandy Pawmpawm beaches there was less than 25 percent cover. Shelter is apparently necessary to conserve finer particles and permit plant growth. In Pawmpawm the drawdown was not cultivated, but the area immediately above was planted in cassava and maize plots.

Drawdown agriculture seemed low in the southern lake, and weed growth partial. In the north, the generally flat

shores from Yeji to above Mpaha had a luxuriant sward of grasses and reeds. Drawdown agriculture was not seen in the north, although this and pastoral use of the vegetation (Richardson, 1970; Hall, 1970; Amatekpar, 1970) have been reported. Floating weeds were not seen below Mpaha although in some areas (i.e., Yeji, Pru River) flooded trees were dense inshore.

Fish

Near Ajena dock, four Tilapia galilaea (10, 10, 5, 5 cm) and a school of about 15, 5-cm Epiplatys were seen in 15 cm water over a barren bottom pockmarked with groups of around 15 holes each, 3 to 5 cm in diameter, perhaps the breeding hollows of cichlids. One dead 5-cm Pellonula, several small 6 to 8-cm Chrysichthys and one 12-cm Tetraodon fahaka were seen on the Pawmpawm shoreline. Clupeids are reputedly abundant inshore there at night, and light attraction methods appeared to be known to the villagers. At one village a basket of perhaps 200 live Chrysichthys (8 to 15 cm) and one 8-cm T. galilaea were suspended in the shallows; these were apparently caught with a small mesh beach-seine and used to bait long-lines for Lates. Such offshore long-lines are apparently increasing in use; lines of corks supporting these extended up to 1 km offshore in several of the Gorge. Here again, one fisherman showed Chrysichthys used to bait the hooks.

The inhabitants, all Tongu Ewes, of five fishing settlements investigated in Pawmpawm, about 500 m to four km apart, had largely switched from fishing to specialist farming (one village producing cassava, the next chiefly maize, etc.). None of the villages showed any sign of fishing activity and few canoes were seen. One or two women in each village were smoking Lates purchased from fishermen in other parts of the bay; modal length was 30 cm, but the fish ranged from 15 to 60 cm long. Long-lining is scarcely size-selective, and although two of the larger fish had ripening ovaries, many must be immature. In one village, three 30-cm T. galilaea were seen, and in another, two of under 15 cm; fishermen indicated that in order to catch larger sizes, a 5-inch mesh net would be required, but that this was not available. Questions about mesh sizes produced vague responses; nets of one to four-inch and one seven-inch mesh were seen in the villages; also cast nets were noted. There was no sign of net-mending at the time of the trip, a distinct difference from field trips in 1966-1969.

Dr. Reynolds was told that fish were more abundant on the west shore of Pawmpawm; this is flatter with dense trees, so the shoreline is therefore less sandy and exposed. Bilharzia too is said to be prevalent among fishermen there, but this might not be a current infection.

During Dr. Reynolds' visit, a 1/2-inch mesh net was put out overnight at Ajena and the catch collected for him. It contained over 1,000 Pellonula and two Physailia (7.3, 7.0 cm); 45 Pellonula were measured (Table 18) and 25 stomaches containing food examined. Sixteen Pellonula stomachs contained termites, ants, chironomid adults and mature pupae (emerging); eight contained plankton (Cladocera), some copepods, and occasional Volvox, and one Pellonula contained other unidentified matter. Those fish that were best preserved, and so were probably caught in the early morning, had almost entirely empty stomachs, whereas the more decayed (the evening catch?) had occasionally some food. Fat levels were copious in all, and gonads were immature or quiescent. The data suggest there has been little dietary change or deterioration in clupeid condition since 1969.

TABLE 18. Pellonula Experimental Catch Data, Ajena[a]

Size Frequency	
Length (cm)	Number
0 - 4.8	3
4.9 - 5.2	24
5.3 - 5.6	10
5.7 - 6.0	5
6.1 & over	3

[a]1/2-inch mesh net.

Fish catches were examined at Yeji; a two-inch series of nets surface-set caught (in order of decreasing abundance), Alestes leuciscus, Eutropius niloticus, Schilbe mystus, Petrocephalus bovei, Cynothrissa mento and Physailia pellucida (one large specimen about 15 cm). Many smoked Synodontis were offered for sale in the markets. The catch composition has thus not changed greatly from other dry seasons, supporting Dr. Reynolds' suggestion that the northern lake would retain a much more riverine character than the south. The Yapei port, of some importance for fish distribution owing to proximity to a major roadhead, was chiefly landing Synodontis and bagrids.

Piscivores

In Pawmpawm Bay and the southern lake, groups of up to 20 small birds, possibly terns, were seen swooping over the lake waters and occasionally picking small objects from the surface. No dead Pellonula were seen floating there, but the birds may have been feeding on drowned insects or on schools of small fish at the surface. They evinced no interest in large flocks of migrating butterflies crossing the lake there. Drowned isolated trees appeared to be used as usual roosts.

Further uplake, occasional cormorants and black herons were seen, but generally speaking, piscivorous bird life was not notable.

APPENDIX 3

Annotated Bibliography of the Hydrobiology of Volta Lake

Prepared by Dr. Mohammed A. Aziz

Introduction

This annotated bibliography of the Volta Lake, Ghana, includes papers in hydrobiology and related fields on the lake and the river above the Akosombo dam. References to the river below the dam have been largely omitted. Work published from 1947 to 1972 is included in the bibliography. There have been relatively few publications on hydrobiological research on the lake since 1972. Various papers on the Volta Lake recently published in Ackermann, W. C., G. F. White, and E. B. Worthington (eds.), Man-Made Lakes: Their Problems and Environmental Effects (American Geophysical Union, Washington, D. C. 1973) were presented originally at the 1971 International Symposium on Man-Made Lakes, Knoxville, Tennessee. Papers presented on the lake's hydrobiology at that symposium are included in this bibliography.

It is interesting to relate the chronology and number of publications on the lake's hydrobiology to the various stages in its formation. Four distinct stages have been defined in the making of a man-made lake ecosystem (SCOPE, 1972, Man-Made Lakes as Modified Ecosystems, International Council of Scientific Unions, Paris, 76 pp.):

Stage I, feasibility studies leading to the decision to build a dam (for the Volta Lake, 1939-1959);

Stage II, design and construction (Volta Lake, 1959-1964);

Stage III, dam filling and ecological instability (Volta Lake, 1964-1967);

Stage IV, adjustments leading to relative stabilization of the lake ecosystem (Volta Lake, 1967 to present).

On the Volta Lake, the greatest number of publications (54) correspond to the years 1967 to 1971, after the lake had filled, during the period of maximum instability leading to relative stability. This was the period of maximum research effort and interest in the lake and included work by both Ghanaian and international scientists. Following is a list of authors' last names, whose work is referenced here, arranged chronologically and subsumed under the four stages mentioned previously.

Stage I Feasibility studies.

1947	Irvine
1954	Daget
1957	Blanc

Stage II Design and construction.

1960	Daget
1962	Daget
1963	Lawson

Stage III Dam filling and period of instability.

1965	Daget Obeng
1966	Beauchamp Biswas, S. Ewer Petr Proszynska Reynolds Roberts Roman Worthington

Stage IV Long-term adjustments.

1967	Biswas, E. Biswas, S. Lawson Petr Reynolds Roberts Wuddah Anonymous
1968	Attionu Biswas, E. Biswas, S. Freshwater Biol. Abstracts Lawson Petr Proszynska Ram Reynolds Thys van den Audenaerde
1969	Adiase Biswas, S. Denyoh Entz FAO Hall Holm Lawson Lelek Obeng Petr Proszynska Rajagopal Reynolds Taylor, B.W. Taylor, G.T. Viner White Whitehead
1970	Biswas, S. Brooks Evans Inst. Aquatic Biology Lawson Obeng Petr Pierce Regier Viner
1971	Biswas, S. Butcher Czernin-Chudenitz Denyoh Evans Hall Pierce Reynolds Vanderpuye
1972	Biswas, E. Biswas, S. Inst. Aquatic Biology Vanderpuye

Adiase, M. K. 1969. A preliminary report on the food of fish in the Volta Lake. In Man-Made Lakes, The Accra Symposium, ed. L. E. Obeng, pp. 235-237. Accra: Ghana Univ. Press.

[An analysis of food habits of some Lake Volta fishes.]

Attionu, R. H. 1968. Some limnological investigations in the Ajena Bay (Volta Lake, Ghana), July 1965 - April 1966. Volta Basin Research Project Tech. Rept., X 26. University of Ghana, 8 pp.

During the rainy season (April-July) there is a rise in the level of the lake due to increased inflow from the rivers; the rise occurs towards the end of the rains (July). Temperature of the water from July to September is low (26-27°C), but it rises to 30°C in October and November. It drops again between December and February followed by a rise in April. In July-September 1965 and December-March 1966, the temperature difference between top and bottom was only 0.4°C but in November it was 3.6°C. The July-September low temperature is due to the cool moist southerly air that blows over the lake; the December-March low is due to the northerly dry "harmattan" winds which cool the lake surface by evaporation. The "cool" periods are characterized by maximum mixing of the water up to 5 m deep. Because the bay is sheltered, complete mixing does not occur; complete mixing does occur in the main channel. There is seasonal variation in the transparency of the water--presumably controlled by the amount of iron in the water. The pH of the water does not vary much because of the high buffering effect of the carbonate-bicarbonate content. The water has adequate silicate and phosphate for the production of phytoplankton. High ammonia concentration was recorded during phytoplankton development. No correlation between oxygen concentration and phytoplankton maxima was found. Annual flooding is very important in the productivity of the lake.

Beauchamp, R. 1966. Dams create unique laboratories. New Scient., 36:376.

A general report on the Symposium on man-made lakes organized by Ghana Academy of Sciences at Accra, Ghana (1966). It is suggested that the man-made lakes may be very valuable "laboratories" where the following aspects of tropical hydrobiology may be studied": (1) Interspecies ("biotic") interactions in a community functioning under relatively constant (physical) tropical environment. (2) The value of the "biological cycle" in tropical waters. (3) Population dynamics of the important commercial fishes, e.g., Tilapia. (4) The differences (and their implications) that exist between the water budgets of natural and man-made lakes.

Biswas, E. R. I. 1967. Bacterial ecology of Volta Lake at Ajena. Volta Basin Research Project Tech. Rept., X 18. University of Ghana. 12 pp.

Observations of weekly bacterial counts throughout the water column of Volta Lake were made at Ajena from August 1964 to December 1965. The results show that during the rainy season bacterial populations increase--the contrary being true in the dry months. The highest counts were obtained from the surface close to the bank, but the difference in population density between the surface and midwater was only small (1.68:1 ratio). This is very different from that reported in some temperate lakes (Lake Geneva 4000:1 and Lake Windermere 200:1). Lake Volta bacteria are dominated by vegetative forms (67%) followed by chromogenic (10%) and small numbers of coliform.

[A valuable report on preliminary studies of bacteria in a tropical lake. Bacteria play a vital role in the breakdown of organic matter and the recycling of nutrients. Very little information on the bacteria of natural lakes in Africa is available.]

Biswas, E. R. I. 1968. Some microbiological observations on the Volta Lake. Ghana Jour. Sci., 9(1):21-29.

Since 1964 heterotrophic bacteria in the lake have been declining. In the same period there has been a shift in their distribution from the surface to the bottom. The influence of temperature and rainfall on the bacteria is not fully known yet. The bacteria consist of mainly chromogenic forms; coliforms remain low. Observations showed that bacteria increased following flooding in July 1965.

Biswas, E. R. I. 1972. Changes in the heterotrophic bacteria of Volta Lake, 1968-1971. Ghana Jour. Sci., 12(1):72-85.

A previous study of the heterotrophic bacteria of Volta Lake has been continued over the final stages of its formation. A regular sampling program was maintained at Ajena and supplemented by occasional samples from stations up-lake. Temperature and Secchi disk transparency increased and their seasonal differences lessened. Bacteria appeared unaffected by changes in temperature while there was evidence of an inverse relationship with transparency in the surface layers. Throughout the period highest counts came from below 20 m. Two or three peaks occurred each year, the main one coinciding with the early rains. The difference in counts from near the shore and from mid-lake was greatest during the early rains and also during the subsequent floods.

Gram-negative rods continued to predominate. Gram-positive spore forming rods were mainly found on the bottom and their general distribution was very variable. Chromogens accounted for about one-fifth of the population. Presumptive coliform organisms decreased steadily until 1970 and then rose abruptly but without evidence of fecal pollution.

Biswas, S. 1966a. Oxygen and phytoplankton changes in the newly forming Volta Lake in Ghana. Nature, 209(5019):218-219.

A resume of changes in oxygen and phytoplankton in the water following the formation of the lake. Prior to the closing of the dam in 1964, the riverine water was super-saturated with oxygen (110-170% saturation). Prior to the closure of the dam, the blue-green alga Anabaena aphanizomenoides Forti was declining, but the formation of the lake (following May 1964) led to a phenomenal increase of the alga accompanied by a rise of oxygen in the lake water to 324% saturation. This rise is attributed to: (a) the super-saturation of oxygen in the river water, (b) photosynthetic activity of Anabaena.

Later in the year, Anabaena declined and oxygen level dropped to 16% saturation (June 19). A succession by another blue-green alga, Microcystis flos-aquae, reached a peak on July 10; oxygen rose to 36% saturation. There was a decline of Microcystis and oxygen reached record low-level on July 31 (10-15% saturation). Later the green alga, Ankistrodesmus falcatus (Corda) Ralph. began to increase; oxygen rose to 33% saturation. On July 31, the water was isothermal at 27.4°C.

[A significant short report on the changes in aeration of water and plankton production accompanying the formation of the lake. A rapid rise in oxygen-level of the water following damming did not last long; an overall diminution of oxygen has occurred in Lake Volta. A clear relationship is established between phytoplankton blooms and oxygen concentration of water.]

Biswas, S. 1966b. Ecological studies of phytoplankton in the newly forming Volta Lake of Ghana. Jour. West African S. Assoc. (Ibadan, Nigeria), 2(1-2):14-19.

Changes in Ammonia (NH_3), Nitrogen-Nitrate ($N\text{-}NO_3$), Phosphate (P_2O_5), Iron (Fe^{++}; Fe^{+++}), and color accompanying the formation of Lake Volta are recorded and related to the production of phytoplankton (Melosira granulata [Ehr] Ralfs; Synedra acus Kuetz; Anabaena aphanizomenoides Forti; Microcystis flos-aquae [Wittr] Kirchn.; Ankistrodesmus falcatus [Corda] Ralfs and Cryptomonas). Changes from September 1963 (riverine) to February 1965 (lacustrine) are

(Biswas, S., 1966b, continued)

plotted on graphs. The following trends are noted:

	1963	1965
NH_3	0.01-0.06 mg/l	0.28 mg/l
$N\text{-}NO_3$	0.05-0.16 "	nil
P_2O_5	0.04 "	0.16 " (July)

From September 1963 to March 1964, phytoplankton was very low (0-17 cells of diatoms/mg), but in May 1964, a bloom of Anabaena (over 10,000 cells/mg) led to a super-oxygenation (over 300% saturation). From February 1964 to February 1965, a steady succession of phytoplankton species was noted; this succession is related to changes in the turbidity of the water as well as to the production and use of oxygen. Biswas (p. 18) explains this as a result of a cycle between ferrous and ferric forms of iron compounds. The ferric condition imparts a brownish opalescent turbidity, cutting down light penetration and thus rapidly reducing the phytoplankton population. This will in turn reduce the dissolved oxygen and under this condition ferric iron will be converted into the soluble ferrous form. The result will be an increased transparency of water followed by phytoplankton growth.

[A fairly detailed account of changes in major ions, light, oxygen and phytoplankton in the lake. Although detailed tables of recorded values of the various ions at different times of the year are not given, the data do permit some tentative conclusions about changes accompanying damming of Volta River. Since all the changes recorded are from Ajena (close to the dam), it is conjectural if these conditions are representative of the whole lake. Further, the fluctuations recorded are not adequately related to the annual flooding cycle of the rivers.]

Biswas, S. 1967. Some limnological innovations. Volta Basin Research Project Tech. Rept., X 19. University of Ghana. 7 pp.

Descriptions of a water sampler, depth correcting gadget, plankton counting cell, substitute battery for pH meter, and lead acetate method for sulfide estimation.

Biswas, S. 1968. Hydrobiology of the Volta River and some of its tributaries before the formation of the Volta Lake. Ghana Jour. Sci., 8(384):152-166.

Hydrobiological conditions in Volta prior to and following damming are presented (Sept. 1963-1964). From Sept. 1963 to Jan. 1964, the Volta River was very poor in phytoplankton, which began

to appear in March 1964 and reached a peak in May. Melosira and Synedra showed earlier peaks, followed by Anabaena.

Upper Volta is richer in phytoplankton than the lower basin. Peaks of Arthrospira appeared at Yeji and a few other northern stations. Reasons for this peculiar abundance are unknown. Tributaries of the Volta are poor in phytoplankton and are dominated by diatoms. Changes in phytoplankton density have caused the oxygen in the water to fluctuate. Quantitative changes in nutrients during the period of investigation also are discussed.

Species of phytoplankton dicussed:

Melosira granulata (Ehr) Ralfs
Synedra acus Ktz.
Anabaena aphanizomenoides Forti
Peridinium africanum Lemm
Cosmarium moniliforme (Turp) Ralfs
Staurastrum paradoxum Meyen
Arthrospira tenuis Bruehl and Biswas
Nitzschia sigmoidea (Nitasch) W. Sm.
Phormidium tenue (Menegh) Gom
Pinnularia stauroptera (Grun) Rabh.
Nitzschia acicularis (Ktz.) W. Sm.
Ankistrodesmus falcatus (Corda) Ralfs

Biswas, S. 1969a. The Volta Lake: some ecological observations on the phytoplankton. Verh. Internat. Verein. Limnol., 17:259-272.

Temperature: In June 1966, the epilimnion was at 31°C and the hypolimnion 27-29°C. At Afram, Kpandu, Kete Krachi, the metalimnion was at 20 m. Ajena did not have a well-defined metalimnion; Yeji had the entire water column homothermal. Periods of greatest circulation were June-September 1966, and January-February 1967. For the rest of the year the lake is stratified. The metalimnion broke down in September 1966, and reformed in April 1967.

Oxygen: In June 1966 dissolved oxygen increased 6-7% in daytime. At the time of greatest circulation, oxygen reaches the bottom. During stratification there is no oxygen below 15 m; the epilimnion has 80-90% saturation.

Phytoplankton: Plankton shows much variation from one station to the next. In July-August 1966, green algae were dominant in the lower part of the lake.

(Biswas, 1969a, continued)

Green algae included Scenedesmus acutus (Meyen) Chod., S. bijugus (Turp.) Ktz., and S. quadricaudus (Turp.) Breb. The diatoms included Melosira granulata (Ehr) Ralfs, Nitzschia acicularis (Ktz.) W. Sm., and Synedra acus Ktz. Various species show different dominance periods in the different stations. Diatoms, however, are becoming increasingly important in the lake.

Biswas, S. 1969b. Thermal changes in the Volta Lake at Ajena. In Man-Made Lakes, The Accra Symposium, ed. L. E. Obeng, pp. 103-109. Accra: Ghana Univ. Press.

The report covers the early development of Lake Volta (1964-1966). During floods (June-August), the epilimnion shows a cooling trend while the hypolimnion warms up. Although mixing occurs, the water was never found to be homothermal--the epilimnion being generally warmer than the hypolimnion. Mixing also occurs in the harmattan season (January-March). For the rest of the year the lake is stratified--with peak temperature in October, November or preceding the flood. The metalimnion was found between 10-35 m. At Ajena there was a general decrease in oxygen following closure, but the situation has improved each year (oxygen concentrations: August 1964 = 19%; August 1965 = 31%; June 1966 = 100%). Much of the oxygen is found in the top 5 m. Even during mixing full oxygenation of the water column does not occur. The lake neither stratifies fully nor does it mix completely.

Biswas, S. 1970. Changes in the phytoplankton of the developing Volta Lake. Ghana Jour. Sci., 10(2):85-92.

The phytoplankton of the developing Volta Lake consisted of more than twice the number of taxa found in the river system before the impoundment. Such an increase in taxonomic diversity was not uniform in all the classes as the green algae increased four times, the euglenoids eight times and the blue-green algae more than twice. The flageliates barely increased while the diatoms decreased due to the disappearance of some of the taxa common in the tributaries. There was a greater abundance of phytoplankton in the lower reaches than in the upper ones. In general, classes of algae represented by a few taxa showed a high density of population. This was especially the case with the diatoms in the lower reaches and occasionally the flagellates in all parts of the lake. In the river the phytoplankton varied from a near absence to a high peak of short duration before the flood. Such extreme variations were not observed in the lake. The peak initially showed no definite seasonal pattern but later it settled to the dry season following the flood. In the lower reaches of the lake the dominant organisms changed from the blue-green algae to the diatoms and then again to the former.

Quantitatively, however, there has been a considerable decline of blue-green algae. Most of the organisms occurred vegetatively in all parts of the lake throughout a year. They were present in all parts of the lake throughout a year. They were present in the upper layers during the months of stratification. Periodic mixing distributed them throughout the depth, especially during the months of floods and wind-action.

Biswas, S. 1971. Limnological observations during the early formation of Volta Lake in Ghana. Paper presented at the Man-Made Lakes Symposium, Knoxville, Tennesee, May 3-7, 1971.

The Volta Lake started forming with the closure of the dam in 1964 and practically reached its full extent in 1968. During this period continuous limnological observations have been possible at an offshore station two miles upstream. The lake filled actively in the flood season and evaporation caused a slight drop in level in the dry season. The flood and northerly harmattan winds regularly overturned the lake. This was evident from a near homothermal condition of the watermass, together with the spread of a brown color, iron, phosphates, ammonia, nitrites and sulphides from the bottom to the upper layers. The brown color was due mainly to colloidal iron and it caused a decrease in the transparency and dissolved oxygen in the upper layers. In the intervening periods the lake showed a tendency to stratify forming a warm metalimnion rich in oxygen but poor in color and mineral substances. In the first two years the hypolimnion was relatively low in temperature and oxygen while high in color and minerals. In the subsequent years these conditions were appreciably reversed probably due to more frequent overturns caused by increasing weather disturbances as well as outflow through the turbines and spillways.

Biswas, S. 1972. During the year, January-March (harmattan season) and July-September (flood season) are periods of maximum mixing in Lake Volta. At these times iron from the hypolimnion comes to surface and forms colloidal suspension of Fe^{+++} making the water turbid. This results in a low Secchi Disc reading and also a lower photosynthetic rate with the consequent drop in oxygen production. Opposite events occur during times of stratification. Prior to damming the river was dominated by green alga Actinastrum gracilimum which disappeared in 1967. Following damming (1965-1966), flagellates Cryptomonas and Peridinium became very common. In the same period Nitzschia acicularis and Synedra acus also consolidated themselves in the lake. A not too well understood connection exists between physico-chemical conditions and the composition of phytoplankton in Lake Volta.

Blanc, M., and J. Daget. 1957. Les eaux et les poissons de la Haute Volta. Mem. I.F.A.N., 50:113-168.

Brooks, M. 1970. A bibliography of hydrobiological work in Ghana--including references to Onchocerciasis, Bilharziasis and Dracontiasis (excluding yellow fever, malaria and trypanosomiasis). Ghana Jour. Sci., 10(1):49-67.

Butcher, D. A. P. 1971. Sociological aspects of fishery development, Volta Lake, Ghana. Paper presented at the Man-Made Lakes Symposium, Knoxville, Tennessee, May 3-7, 1971.

Volta Lake (3,250 sq. mi. in area) began forming in 1964 on completion of Akosombo Dam. The former riverine fishery was worked by 2,000 fishermen whose numbers are now over ten times as many. Although the fishermen do financially well in comparison with most farmers, it is considered that the lake is underfished (1970) and that the catch rate can be increased in several ways. The two ways to be investigated first are: (1) increase in catch per unit effort, and (2) regular fishing of all parts of the lake. Increases in catch are not merely dependent upon the physical capabilities of the gear used but on the characteristics of the people who are to make use of the gear.

It is assumed that since the total factors in the fishery system in existence during 1970 are in equilibrium in socio-economic terms, it follows that the introduction of any innovation can alter the equilibrium either to a new favorable point or to a worse position. The acceptance or rejection of new ideas in the Volta fishery were dependent on many factors, the most important of which were: (1) fishing methods in use at present; (2) goals and aspirations of the fishermen; (3) composition and organization of the work team; (4) acquisition of capital, interest rates, and method of repayment; and (5) idea or technique to be introduced is technically sound for the particular environment.

The criterion for success must be the increase in income to the human population at present benefiting from the fishery. Judgments by other standards or other idea systems are disregarded. Accordingly the benefits must include social benefits such as the maintenance of the family work units as at present or with no detrimental disruption. Initiative and ownership of boats and gear is probably best left in the hands of owner-operators. The first innovations evaluated are the introduction of monofilament nets and more seaworthy canoes.

Czernin-Chudenitz, C. 1971. Recent limnological status of Volta Lake, Ghana. Paper presented at the Man-Made Lakes Symposium, Knoxville, Tennessee, May 3-7, 1971.

Limno-chemical observations, mostly at two-month intervals, along the main axis of the lake were carried out for a period of two years (1968/70). Changes in different aspects of physico-chemical conditions due to two main seasons, dry and rainy, were recorded each year. The oxygen conditions are still improving and are in close relationship to the temperature. The thermocline is descending to greater depths. Starting at 17 m in 1965, it was 27 m in 1968, and in 1970 it was in the 30 to 35-m range. The difference in temperature between surface and bottom is low (about 3°C). The difference in temperature between upper and lower borderline of the thermocline is 0.4°C only. Partial mixing is therefore possible at any time. Total mixture occurs mainly during the rainy season and during "harmattan" time. The deepest parts of the southern lake sections are not regularly influenced by mixing. Most of the time there is a completely deoxygenated water layer just above the old river bed.

Nutrients: Just after filling started, the lake was very rich in nutrients which resulted in an enormous peak of phytoplankton. With the progressive decay of the flooded vegetation, especially the flooded trees, the open water is now relatively poor in phosphates and nitrates. Sources of the nutrients are from the hypolimnion during mixing, the shallow water areas with their decaying weeds, and the yearly flood. Total alkalinity is very low.

The flooded trees are still present throughout the lake, although some have been under water for seven years. At first, these trees were abundantly inhabited by mayfly larvae, but the larvae were recently found now to use *Polygonum* beds most abundantly for feeding and breeding.

Beds of aquatic weeds, mainly *Pistia*, started to grow first in the upper parts of some tributaries in shallow water. In the two years of observation, *Pistia* has become completely displaced by *Vossia* and *Polygonum*.

Ranking first in numbers as well as in weight among the fishes are the non-commercial species of the family Clupeidae (*Pelonulla* and *Cynothrissa*), which are the main food for the Nile perch, *Lates*. *Lates* prefers mainly the deep and open water. *Tilapia* is abundant in shallow and sheltered water areas. In the northern part of the lake, fish of the riverine type are dominant.

Daget, J. 1954. Les Poissons du Niger Superieur. *Mem. I.F.A.N.*, 36:391.

Daget, J. 1960. Poissons de la Volta Noire et de la Haute Comoe. Mission d'Aubenton-Arnoult, Oct.-Dec. 1959. Bull. Mus. Nat. Hist. 2e Ser. Tome 32(4):320-330.

Daget, J. 1962. Les Poissons du Fouta Dialon et de la Bassée Guinée. Mem. I.F.A.N., 65:210.

Daget, J., and A. Iltis. 1965. Poissons de Côte d'Ivoire (eaux douces et sauma tres). Mem. I.F.A.N., 74:385.

Denyoh, F. M. K. 1969. Changes in fish population and gear selectivity in the Volta Lake. In Man-Made Lakes, The Accra Symposium, ed. Obeng, pp. 206-210. Accra: Ghana University Press.

The nets show some specific size composition in their catches according to mesh size. (a) 1 1/2 to 2" nets: Alestes nurse, Alestes dentex, Alestes macrolepidotus, Hydrocyon sp., Lates niloticus, Ctenopoma kingsleyae, Synodontis nigrita. (b) 3" nets: Labeo senegalensis, L. coubie, Tilapia galilaea, T. zillii, T. nilotica. In deeper water Synodontes and Lates are caught. (c) 4" nets: Clarias spp., Lates, Distichodus spp. and Synodontis in deeper water. (d) 5" nets: Clarias spp., Heterotis niloticus, Labeo spp.

Denyoh, F. M. K. 1971. Fishery development, Volta Lake, Ghana. Paper presented at the Man-Made Lakes Symposium, Knoxville, Tennessee, May 3-7, 1971.

When Volta Lake started to form in 1964, it brought about a major revolution in the fishery of the Volta River Basin. Before the construction of the Volta Dam at Akosombo and its subsequent formation of the lake, there were not more than 2,000 fishermen operating in the Volta basin. These fishermen were mostly nomadic and lived in temporary huts scattered along the main river and its main tributaries, namely the Black Volta, White Volta, Oti, and Afram. The Sene, the Dwija and the Obosum rivers were just small streams which did not support any significant fishery.

Fish catch and fishing village surveys conducted in 1968 and 1969 revealed at least 10,000 fishing villages with 20,000 fishermen scattered along the lake shore. Canoe counts gave a result of between 11,000 and 14,000 fishing canoes and lead to estimates of catch in 1969 of between 50,000 and 70,000 metric tons, as compared with an annual take of about 10,000 metric tons from the previous riverine fishery. As the ecology of the whole Volta basin changed, so did the fish population. The relative abundance of species changed drastically with Tilapia species now forming more than 50 percent of processed fish entering the major fish markets along the lake. Other commercially important fishes like Lates niloticus and species of Labeo, Distichodus, Citharinus, and catfishes also have relatively increased in population from the former riverine conditions.

Before the formation of the lake, multifilament nylon gill nets had replaced the old cotton nets in use a few years back. When the Volta Lake Research Project commenced, a series of comparative fishing experiments were carried out with multifilament nylon nets and monofilament nylon nets to compare their efficiency (monofilament nets are not yet in use in Ghana). Both types of netting materials were constructed to the same specifications, and were joined end to end during the fishing operations. Shallow inshore waters as well as deep offshore waters were fished. The results of this experimental fishing were conclusive in showing that monofilmanet nets are far superior to multifilament nets in fishing efficiency for the important species of commercial fishes in the lake.

It was also found that change in the prevalent methods of hanging nets could improve the catch. Traditionally, local fishermen do not use enough floats on their surface nets when setting them. They use on the average very few floats, spacing them 30 to 50 yards apart, resulting in a considerable sagging of nets in the water. Experiments have proved that by using more floats and therefore avoiding sagging, the catch is increased by at least 50%.

There are also indications that fish inhabit very deep waters of the lake, sometimes to 100 ft or more. By sinking gill nets in these deep waters, some of the important commercial species inhabiting these depths can easily be exploited.

Trap fishing has rapidly become very popular, especially for inshore Tilapia. Traps are made of cane or wire netting. Gill nets do not seem very efficient in the exploitation of Tilapia and hence most of the Tilapia fishing is done with traps, mostly during the dry season when the lake level starts to fall and its waters recede from flooded vegetation.

The bulk of the fish which get to the market are those already processed by smoking or by salting and sundrying. Almost all processed Tilapia are salted and sundried. The other species are mostly smoked. Attempts are being made to improve the quality of processed fish in its present form by reducing the salt content and by making smoked fish drier but avoiding cooking during smoking.

Completely new fish markets which did not exist before have come into being since the formation of Volta Lake. Four of these are major markets--Kpandu and Abotoase on the Eastern shore, Yeji in the north, and Adoroso on the Afram arm. In between these major markets there are many small ones scattered along the lake shore.

(Denyoh, 1971, continued)

A large fleet of transport canoes (ocean-beach canoes powered by outboard motors) has developed at these major market centers. These transport canoes convey, on the average of twice weekly, fish loaded in baskets and fish sellers from the various fishing villages to these fish markets. From the fish market a number of "mammy" trucks carry the fish to the big towns in the various parts of the country.

It is interesting to note that the Volta Lake has brought about a complete change of occupation of most people residing along the lake. Women who were once engaged in pottery work or farming are now fish-mongers, and many men who used to be farmers have turned full-time fishermen. It has also resulted in a wholesale population movement from one section of the country, Lower Volta District, to areas along the lake.

Entz, B. 1969a. Limnological conditions in Volta Lake, the greatest man-made lake of Africa. Nature and Resources (Bull. Int. Hydrol. Decade), UNESCO, 5(4):9-16.

The Volta Dam at Akosombo was closed May, 1964 and the lake reached its maximum height in September, 1968. Due to its shallowness 80% of the total water mass is suitable for habitation by aquatic organisms (including fishes). The lake has a shoreline 5,300 km; the mean depth of the main arm is 18.9 while that of the tributary basins is 6.9 m.

Temperature and Oxygen: 1964-1966 oxygen was found only in the top 5 or 10 m; the lake was as a whole, oxygen deficient. In this period very little change in oxygen quantity occurred. 1967-1969 oxygen in the water increased and seasonal variations became apparent. In the top 20-30 m oxygen attained 50-100% saturation. The lake began to circulate periodically allowing oxygen to reach the bottom.

Observations suggest that phytoplankton does not contribute significantly to the oxygen content of the water. Wind action remains the key to oxygenation of water. A steady breeze of 4-5 m/sec can oxygenate water quite rapidly. Rapid changes in the quantity of gas at various depths are characteristic. It is expected that with time the lake will become even more aerated than it is at present. The temperature of the water varies between 27-31°C; diurnal overturns occur in the shallow water zone.

Effect of Rainfall: Locally, there is a drop in temperature, introduction of solids, colloidal and dissolved matter, and increase in turbidity. Regionally, there is flooding of msot rivers feeding into the lake. Nutrients are introduced into and the main arm becomes turbid.

Division of Lake Volta: (1) Lower Basin (south of Kpandu) is the lacustrine section; S.D. reading = 200-400 cm. (2) Middle Basin (Kete Krachi to Kpandu) is lacustrine during the dry season (November-June) and riverine during the wet season (July-October). (3) Upper Basin (north of Kete Krachi) is semi-riverine all year.

Chemistry: Chemically Lake Volta is oligotrophic; sulfate and chloride ions are low in the water. The metalimnion is also the "chemocline." The epilimnion (pH = 7.5) is poorer in nutrients than the hypolimnion (pH = 6.7). The content of iron below the metalimnion is high--1 to 30 mg/1. In the epilimnion it is 0 to 0.2 mg/1.

Entz, B. 1969b. Observations on the limnochemical conditions of the Volta Lake. In Man-Made Lakes, The Accra Symposium, ed. L. E. Obeng, pp. 110-115. Accra: Ghana Univ. Press.

Using "Maucha diagrams" the chemical composition of Rivers Dayi and Volta and the newly formed Lake Volta is compared. The Volta system waters are of the Ca-HCO_3 group of β-limno type while those of River Dayi belong to the Ca-Na-HCO-Cl group of the β-limnohaline type.

In October 1966, there was very little difference in chemical composition of water from a given layer at various localities. However, HCO_{3-}, CO_2, Ca^{++}, Fe^{++}, NH_{3-} increase with depth while O_2, pH and temperature decrease. SO_{4-} and NO_2NH_3 were also recorded. The water of Lake Volta is as a whole reductive.

Evans, W. A., and J. Vanderpuye. 1970. Early development of the fish and fisheries of Volta Lake, Ghana. Volta Lake Research Project, Cyclostyled Rept., 16 pp.

The following data on the present fishing activity on Volta Lake are given: 12,500 plank canoes; 25,000 fishermen; 900 fishing villages; 1969 catch = 60,000 metric tons; principal species caught include Tilapia, Labeo and Lates. The fishery is restricted to 1,000 mile wide margin along the littoral and an estimated 4 canoes per square mile use this region.

Most of the fishing activity is carried out in the wet season when fish (particularly Tilapia) are most abundant in the littoral zone; in the dry season Tilapia move into deeper water and operations come to a near halt.

The fishery is not being fully utilized owing to inefficient gear, effort and the difficulty of fishing in areas with flooded trees. Fishermen commonly use static, coarse-meshed (size 14 cm) gill nets which are mostly set in 5 m of water.

(Evans and Vanderpuye, 1970, continued)

The aim of this investigation was to assess fish stock in Lake Volta. Direct estimation of the stock is impossible under the present conditions. The authors recommended that an assessment be obtained by indirect means, e.g., through the expansion of the present fishery until changes in catch in relation to effort, size or species composition begin to change.

The investigators carried out sampling on the lake at various stations and attempted to correlate their catches with those reported in the commercial fishery.

Changes in fish stocks: The anoxia that accompanied the initial filling of the lake (May 1964) caused much Chrysichthys sp. mortality; with maturation the lake water has improved in aeration (79% of the lake volume is now aerated, 1970). The fishery of Volta River was dominated by Labeo, Chrysichthys and Alestes. Lacustrinization has reduced these species in the south, but in the riverine north they still persist. The cichlids have become very successful in the south. The mormyrids--another important family of the riverine fauna--have nearly disappeared from the lake. The open water (pelagic) habitat has been increasingly colonized by Cynothrissa , Pellonula, Eutropius and Physailia. A similar increase is also evident in Lates, Labeo and Distichodus.

Present species composition (1969-1970): At present the clupeids Cynothrissa, Pellonula) represent 3/4 of the fishes in number and 1/4 of the total ichthyomass in the lake. This vast resource is not commercially utilized. Fishes of Lake Volta can be grouped into the following "eco-groups": aufwuchs-detritus herbivores, piscivores, semi-pelagic omnivores and benthic omnivores. Of the semi-pelagic fishes the clupeids account for 99% of the ichthyofauna by number and 1/2 of the total ichthyomass in that "eco-group."

The herbivores (Tilapia, Labeo, Distichodus, Citharinus) form 3/4 of the total commercial catch but represent only 1/4 of the total ichthyomass. Tilapia forms 1/2 of the total commercial catch but only 10% of the ichthyomass. The piscivores form 1/5 of the total ichthyomass. The development of fish stocks shows that it increased from 1964 to 1969 but following this phase the stocks have been reduced--not by overfishing, but by the general stabilization of the lake itself. The fishery of Lake Volta is concentrated in the wet season when the turbidity and the water is high. In the dry season Tilapia migrate into deeper water and are unavailable to fishermen.

The report includes data on relative abundance as well as length frequency, distribution, etc.

Evans, W. A., and J. Vanderpuye. 1971. Fish populations sampling at Volta Lake, Ghana, 1969-1970. Paper presented at the Man-Made Lakes Symposium, Knoxville, Tennessee, May 3-7, 1971.

For determining the species composition and relative abundance of the fish population in the recently formed Volta Lake, emphasis was placed upon obtaining data that would be useful in guiding the development and management of the lake fisheries.

Initial effort consisted of devising a system of sampling related to the lake conditions and available facilities. This consisted of fishing a battery of 45-gill nets ranging in square-mesh sizes from 1/2 to 8 inches at various designated stations throughout the lake 3 times each year in 1964 and 1970. Sampling with rotenone was added to a supplement during 1970.

It is anticipated that comparable monitoring of the fish population will be undertaken on a continuing basis, especially during these initial years while the population is likely to be very unstable. Comparison of the data with catch statistics from the commercial fishery disclose trends of over- or underexploitation of species stocks.

Ewer, D. W. 1966. Biological investigations on the Volta Lake, May 1964 to May 1965. In Man-Made Lakes, ed. R. H. Lowe-McConnell, Symp. Inst. Biol. No. 15, pp. 21-31. London: Academic Press.

In the early months of its formation the following water weeds were noted on Lake Volta: Lemna, Pistia, and Ceratophyllum. There was no explosive development of these weeds.

Soon after closure, the oxygen content rose suddenly to over 300 percent saturation; within 4 weeks it dropped to 16 percent saturation on the surface while no oxygen was found below 10 m. Oxygen content is related to phytoplankton activity (Secchi Disc reading = 1 m). Stratification of the lake is noted. Temperature as well as chemical factors show this (epilimnion 0-10 m; metalimnion 10-25 m; and hypolimnion $25m^{+}$). Measurements of iron suggest extensive mixing in the lake; details, however, are not known yet. Benthos is limited to the top 4-5 m. The initial deoxygenation of the lake led to mass mortalities of Chrysichthys. Initial catches show Alestes, Hydrocynus, Lates, Labeo, Clarias, and Chrysichthys as dominant fishes. Finally the effect of damming on clam Egeria is noted.

FAO (Food and Agriculture Organization of the United Nations, Rome). 1969. Report of the Ad hoc consultations by West African fishery officers on problems of inland fisheries. FAO Fisheries Reports, No. 79, Accra, Ghana, March 29, 1969.

FAO. 1971. Physico-chemical conditions of Lake Volta, Ghana. FAO United Nations Development Programme Tech. Rept., 1 (FI:SF/GHA), p. 77.

Temperature: In terms of temperature, the lake is divisible into the following parts: (a) Northern, which is riverine, homothermal all year and holomictic; 40 percent oxygen in the water and found at the bottom; in the flood these conditions extend down to Oti. (b) Southern, which is lacustrine, stratified quite often with the metalimnion between 20-25 m, and a more superficial discontinuity in the daytime; maximum mixing periods are in the flood and harmattan seasons. (c) Inundated riverine arms which are shallow and limnologically similar to the main lake. The metalimnion is at 8-9 m, and some parts overturn quite often.

Transparency: This is influenced by the following factors: colloidal organic and inorganic (particularly iron) particles and by phytoplankton. The influence of transparency on fish catch needs further study.

Oxygen: At Afram and Kpandu oxygen is found down to 40 m in the floods and harmattan period. Yeji has oxygen all year. Low oxygen values are recorded for the shore stations because of seclusion from wind. The gas is low in the weed beds, but is often recorded below them. Wind remains the most important factor in aeration of lake water. Phytoplankton does contribute to aeration of water, but only on the surface. As the lake has matured aeration has improved.

Chemistry: Very brief notes are given on the distribution of various ions in the lake.

Primary productivity: This can be assessed by oxygen demand; alkalinity; phytoplankton and aquatic weeds. The annual drawdown will contribute to productivity of the lake.

Secondary productivity: This is estimated to be higher in the littoral compared to the pelagic region of the lake.

Aquatic weeds: These are discussed briefly.

Freshwater Biology Abstracts. 1968. Ghana Jour. Sci., 8(1&2):14-16.

Very short abstracts of the biological work on Lake Volta. These abstracts are from reports presented at the 5th Biennial Conferences of the Ghana Science Association (December 27-30, 1967).

Hall, J. B., E. Laing, M. Hossain, and G. W. Lawson. 1969. Observations on aquatic weeds in the Volta Basin. In Man-Made Lakes, The Accra Symposium, ed. L. E. Obeng, pp. 331-336. Accra: Ghana Univ. Press.

An account of the aquatic weeds of Lake Volta with a list of species found in various habitats and formations. Experiments on growth of *Pistia* and observations on "sudd" formation.

Hall, J., P. Pierce, and G. Lawson. 1971. Common Plants of the Volta Lake. Legon, Ghana: Department of Botany, University of Ghana, 123 pp.

The most complete list of common aquatic and semi-aquatic plants of Lake Volta.

Holm, L. G., L. W. Weldon, and R. D. Blackburn. 1969. Aquatic weeds. Science, 166:699-709.

Includes a note on the increase of the floating water weed, *Pistia stratiotes*, in Lake Volta.

Institute of Aquatic Biology. 1969-70. Fourth Annual Report. Council for Scientific and Industrial Research. 109 pp.

Includes resumés of biological work of Lake Volta and other freshwater bodies in Ghana (1969-70). Lake Volta work includes: limnology, water weeds, algae and phytoplankton, zooplankton, aquatic invertebrates, fishes.

Institute of Aquatic Biology. 1972. Some Freshwater Fishes of Ghana. Council for Scientific and Industrial Research, Achimota, Ghana, 13 pp. (IAB 41).

A list of some freshwater fishes of Ghana.

Irvine, F. R. 1947. The Fish and Fisheries of the Gold Coast. London: Crown Agents for the Colonies, 352 pp.

Lawson, G. W. 1963. Volta Basin research project. Nature, 199(4896): 858-859.

A brief note on the formation of Lake Volta and its possible effects or benefits. Includes the following: hydro-electric production; estimated aluminum production at 120,000 long tons/annum; freshwater fishery; inland water transport system; relocation of local population; medical problems (schistosomiasis and onchocerciasis); aquatic weeds; and possible effects of flooding on plankton and fish products. Pre-lake fishery of Volta is estimated at $260,000 per annum. River clam (*Egeria radiata*) production high in the dry season when river is low.

Lawson, G. W. 1967. "Sudd" formation on the Volta Lake. Bull. de l'I.F.A.N., Tome XXIX, Ser. A, No. 1, pp. 4.

A short report on the formation of "sudd" on Lake Volta. Although species of Eichhornia crassipes and Salvinia auriculata exist in the Volta basin, they have not become "weeds." When the dam was closed in May 1964, mats of Pistia stratiotes and islands of "sudd" (Vossia cuspidata and others) appeared in the lake--particularly at Afram. At Ampem, a mat of Scirpus cubensis and other species appeared between crowns of drowned trees. A development of subaquatic plants--Ceratophyllum and Utricularia--is also noted.

Aquatic weeds are very important for the fishes in any tropical lake. An explosive development of weeds leads to loss of nutrients, oxygen, etc.; however, a limited development leads to the formation of rich periphyton and "periphytic benthos" on which many fishes feed.

Lawson, G. W. 1970. Lessons of the Volta--a new man-made lake in tropical Africa. Biol. Conservation, 2(2):90-96.

Summary of changes in Lake Volta since its formation. The paper reviews all salient literature on limnology, water weeds, algae, fishes, etc.

Limnology: In the rainy season cool and oxygenated water enters the lake; stratification is broken down. The turbidity of water increases. Following flooding the water clears up and phytoplankton blooms form. Stratification is re-established.

Plankton: Phytoplankton: blue-green algae predominate in shallow water while diatoms are more numerous in deep water. Zooplankton: rotifers are the dominant component.

Macrophytes: The flooded macrophytes are being utilized by Tilapia zillii, Alestes macrolepidotus, Synodontis spp. The flood plain also provides breeding grounds for many Volta fishes. Annual drawdown will expose 518-1036 km^2 of the lake bottom--renewing productivity annually.

Explosive development of water weeds, e.g., Scirpus cubensis and Vossia cuspidata, has occurred only locally in some cases (e.g., Afram). Pistia stratiotes and Ceratophyllum demersum have also increased. These are eaten by Alestes macrolepidotus and Distichodus spp. The real significance of these macrophytes lies in the rich invertebrate faunas they support. Invertebrates are also richly developed on the surfaces of the drowned trees. These invertebrates support many insectivorous fishes in the lake. The increase of algae in the lake has helped several species of microphylophagous Tilapia.

Lawson, G. W. et al. 1968. A review of hydrobiological work by the Volta Basin Research Project, 1963-1968. Volta Basin Research Project Tech. Rept., X 25. University of Ghana, 4 pp.

The temperature of water in Lake Volta varies between 26-31°C annually. The coolest months are July-August and January-February. In the north, temperature is higher than the south. Oxygen concentration also shows seasonal trends--it is minimum during the floods (April-July) and during the "harmattan" period (September-October) when mixing is maximum. Highest oxygen is recorded in the epilimnion during maximum stratification (in May and November). During this period the metalimnion is at about 20 m. Plankton and fishes do not generally occur below the metalimnion because of the lack of oxygen. Temporary stratification up to 5 m deep forms and breaks down diurnally.

Microbiology: The bacteria count is highest in the epilimnion all year round except in September. In 1965, highest count of bacteria was associated with the rainy/flood season. Bacteria are mainly heterotrophic.

Phytoplankton: Prior to the formation of the lake peaks of *Anabaena* occurred; however, since damming *Synedra* and other species have shown great periodic blooms. Phytoplankton is maximum during stratification and diminishes in the "mixing" seasons. The productive shallow water is dominated by *Myxophycaea* while diatoms dominate the deeper water.

Macrophytes: The most significant of these are *Pistia* and *Ceratophyllum* These act as substrate for the rich aquatic invertebrate fauna that has developed in the lake. *Ceratophyllum* is also the cause of the great increase of periphyton in the lake. *Pistia* and *Ceratophyllum* increase following the flood and these changes are also reflected by the invertebrate fauna.

Aufwuchs: This includes periphyton as well as the invertebrate fauna associated with it. The increase of periphyton is mainly due to the presence of submerged trees in the lake. These have acted as a substrate for the growth of periphyton as well as the success of wood-boring insect-larvae, e.g., *Povilla adusta*.

Zooplankton: Of the planktonic crustacea, the copepods dominate the cladocerans. By 1967, 90% of the zooplankton was composed of Rotifera; 10% is formed by the crustaceans and ciliates.

Benthos: Between 1964-1966, the benthic fauna was restricted to the surface oxygenated zones of the lake only. But as the lake gets more oxygenated, it is expected to penetrate deeper. Much of the benthos is composed of chironomid larvae.

(Lawson et al., 1968, continued)

Epiphytic "benthos": The success of Povilla adusta on tree surfaces in the lake has been mentioned. At present the biomass of Povilla far outstrips that of the benthic organisms, e.g., chironomid larvae.

While some families of riverine fishes have disappeared from the lake, the characids now dominate the lake in the north (over 51% of the total catch) while the cichlids dominate the south (over 65% of the total catch). Some pelagic clupeids and characids have also increased in the south.

Lawson, G. W., T. Petr, S. Biswas, E. R. I. Biswas, and J. D. Reynolds. 1969. Hydrobiological work of the Volta Basin Research Project, 1963-1968. Bull. de l'I.F.A.N., Tome XXXI, Ser. A, 3:965-1003.

A summary of hydrobiological work of the Volta Basin Research Project (University of Ghana) from 1963-1968. Most of Lake Volta lies in the single rainfall Guinea Savanna zone; only its southern extremity (Afram arm) lies in the Antiaris-Chlorophora tropical forest. Rainfall occurs between July-September; the floods occur towards the end of the season. From December-January, the lake is under the influence of the dry northerly "harmattan" winds. The rest of the year south-westerly winds dominate.

Limnology (physical/chemical):

(a) Short-term changes.--All important limnological changes can be related to the rainy season (June-September) and the dry "harmattan" season (December-January). With the approach of the rainy season, the temperature of the river (32°C) and the lake (31°C) rise to a maximum. Temperature is high again in November following an interim fall. In the cool period (September-October, and January-March) water temperature drops to 27.2°C-27.8°C.

During the flood and "harmattan" seasons the lake experiences maximum turbulence and break-down of stratification. Ammonia and iron (Fe^{++}) increase; the latter increases turbidity. Oxygen content of the water goes down but the lake is enriched by nutrients released from the hypolimnion. These effects are more marked in the flood than in the "harmattan" season. Calcium, potassium and sulfide do not exhibit much seasonal variation; however, nitrate is highest between September-December.

(b) Long-term changes.--As the lake has matured, its water has become increasingly clear (Secchi Disc readings 1965: 50 cm; 1967: 400 cm). Prior to flooding Volta River was supersaturated with oxygen (over 100%); as soon as the dam was closed (May, 1964) there was a phenomenal rise of the gas which later dropped to below 100% saturation. In the earlier phase, the lake was devoid of oxygen below the epilimnion, but with maturation and increased circulation, the gas is reaching deeper. Hydrogen sulfide has fallen--particularly since 1965. When the dam was closed the temperature of water fell to 27°C and continued to fall in the hypolimnion, but by October 1964

it began to rise. Since 1965, the bottom temperature stabilized around 27°C. Surface temperature fluctuates much more seasonally. During stratification the metalimnion is at 20 m. Alkalinity increased gradually until 1966, when it became stable but orthophosphate has fallen.

Microbiology: The micro-organisms (bacteria) show high densities on the surface and bottom, being low mid-water. Most belong to the Aerobacter group; no nitrifying agents are reported. Since 1967 the microfauna is on the decline. Almost 1/4 of the colonies are chromogenic (90% Gram negative rods). Spore forming bacteria show great fluctuation during a single year.

Phytoplankton: The primary productivity varies in different parts of the lake; it is estimated between 0.8 and 5.2 g cm^3/24 hrs (oxygen utilization). The productivity of the littoral region is much higher than that of the deeper areas. The composition of phytoplankton has undergone long-term fluctuations; such fluctuation is also evident during each year:

1965	two maxima:	April	- *Actinastrum*
		Sept.	- *Cryptomonas*
1966	three " :	March	- *Peridinium*
		July	- *Peridinium*
		Oct.	- *Nitzschia*
1967	two " :	May	- *Synedra*
		Nov.	- *Synedra*

Phytoplankton is low during the flood and high between October-November; the rest of the year it remains at moderate or low concentration. Low temperature, light intensity and high turbidity of water discourage phytoplankton. In the flood much dilution of phytoplankton is evident. Superifically it seems that diatoms predominate in deeper water while Cyanophyceae are more common in shallow water.

Phanerogamic vegetation: The non-aquatic trees which have been drowned support a rich periphyton. A number of aquatic invertebrates use these tree surfaces for burrowing and as a source of food. Of particular importance is the increase of *Povilla adusta* Navas which has become an important food of many fishes. The flooding of the Volta Basin created a permanent inundated plain rich with grass cover and debris. The plain is used for reproduction as well as a source of vegetative food by macrophytophagous fishes, e.g., *Tilapia zillii*, *Alestes macrolepidotus*, etc.

The lake will have an annual drawdown of 1.5 m which will annually expose 200-400 sq miles of the bottom. Periodic drying will be beneficial for the fishes.

(Lawson et al., 1969, continued)

Other significant plants include Vossia cuspidata, Navas spp., Ceratophyllum demersum and Pistia stratiotes. The latter two are very important habitats of invertebrates. Several of these use them as a source of food (e.g., pyralidids). Pistia attains a dry weight of 500 g/m^2. The aquatic macrophytes increase following the flood and then subside later in the year.

Aufwuchs has increased greatly in the epilimnion, but is used by only a few species of fish. But it supports a large invertebrate fauna which maintains much of the lake's fish production.

Zooplankton: When the dam was closed crustacean zooplankton were found throughout the water column. From July 1964 they have exhibited periodic appearance only. The populations do not seem to develop in situ, but come from the north. From 1965-1966, Copepods (Cyclops, Diaptomus) were most numerous at all depths; cladocerans (Diaphanosoma, Ceriodaphnia, Bosmina, Moina, Bosminopsis) are fewer and restricted to 5-15 m depths. In 1967 at Ajena and Afram, the zooplankton consisted of 90% Rotifera and 10% Crustacea and Protozoa. Rotifers include: Anuraeopsis, Polyartha, Trichocera and Keratella.

The invertebrates associated with Pistia include anisopteran nymphs, larvae, coleopterans, etc. The biomass of invertebrates on leaves was 57.50 gr/kg, and on roots 107.27 gr/kg. The invertebrates associated with Ceratophyllum include zygopterans, chironomids and laccophilus beetles, as well as oligochaetes. Biomass of invertebrates was 76.75 gr/kg (inshore).

Benthos: In 1964-1966 benthic fauna was limited to the epilimnion (3-7 m). Since 1967 with better oxygenation in the deeper water, they have extended their distribution down to 10 m. In 1966-1968 the benthic fauna consisted of chironomids 58.96% and Povilla 30.17%. As the lake stabilized, the benthos began to show a vertical migration seasonally--it is deeper following mixing of water and in shallow water during stratification.

Fishes: The fishes of River Volta were mostly bottom living, insect-feeding species. But the formation of the lake has favored pelagic species (Pellonula afzeliusi, Physailia pellucida, etc.). The mormyrids--which were very significant in the river in the dry season--have become very rare in the lake. The fishery picture of Lake Volta is as follows: in the northern (riverine) basin, Characidae form 51% of the total catch; in the southern (lacustrine) basin, Cichlidae form 81% of the total catch.

All Lake Volta fishes can be placed in the following trophic groups:

(1) Macrophytophagours	18.9%
(2) Insectivorous (aquatic)	18.3%
(3) Piscivorous	13.1%
(4) Detritophagous	13.1%
(5) Insectivorous (terrestiral)	11.3%
(6) Planktivorous	9.2%
(7) Aufwuchs	2.7%
(8) Zooplankton	1.4%

Finally the report discusses some changes in River Volta below the dam.

Lelek, A., and A. A. Wuddah. 1969. A note on the occurrence and length frequency distribution of Tilapia species caught in gill nets in Volta Lake. In Man-Made Lakes, The Accra Symposium, ed. L. E. Obeng, pp. 186-189. Accra: Ghana University Press.

Using gill nets of various mesh size, the following data on Tilapia spp. catch are recorded:

Tilapia galilaea	55.9%
T. nilotica	23.4%
T. melanopleura	20.7%
T. zillii	----

Obeng, L. E. 1965. Preliminary observations on the aquatic fauna of the Volta Basin. Ghana Jour. Sci., 5(3-4):273-274.

[A brief account of the distribution and occurrence of Simuliidae and freshwater molluscs in Volta Basin.]

Obeng, L. E. 1969. The invertebrate fauna of aquatic plants of the Volta Lake in relation to the spread of helminth parasites. In Man-Made Lakes, The Accra Symposium, ed. L. E. Obeng, pp. 320-325. Accra: Ghana University Press.

[Gives a list of invertebrates associated with the aquatic weeds Pistia and Ceratophyllum.]

Obeng, L. E. 1970a. Volta Lake research, a case study of man-made lakes. Paper presented at the Man-Made Lakes Symposium, Knoxville, Tennessee, 1970.

[A general description of problems of man-made lakes.]

Obeng, L. E. 1970b. Man-made lakes, their ecological implications and national development. Paper Presented at the First Commonwealth Conference on Development and Human Ecology, Malta, 18-24 October 1970.

[A general description of problems of man-made lakes.]

Petr, T. 1966. Fish population changes in the Volta Lake over the period May 1965 - July 1966. Volta Basin Research Project Tech. Rept., X 14. University of Ghana, 4 pp.

Changes in the fish fauna and fishery in Lake Volta following the completion of Volta Dam are outlined; data were collected from Akosombo, Ampem, Kpandu, Kete Krachi and Yeji. Because of differences in the location of these sites in relation to the dam and also of the physical nature of the lake shore around each one of them, fish species do not exhibit a uniform pattern of success. At Kpandu and Ampem (both shallow water and partially cleared of vegetation) considerable development of phytoplankton resulted in the drowned forest beaches and this favored a substantial increase in the populations of cichlid fishes (Tilapia spp., Pelmatochromis spp.). In various localities the cichlids accounted for over 50% of the fish catch in early 1966. Data on other fishes are summarized below:

Citharinidae (Citharinus, Distichodus): no substantial change following formation of the lake.
Centropomidae (Lates): has increased in the lake.
Mochocidae (Synodontis spp.): have declined in the south, but no change in the north.
Schilbeidae: many species have decreased in the south, but they retain their strength in the north; only Physailia pellucida has increased in the southern portion following damming.
Bagridae: no substantial change except that Chrysicthys has increased in the south--replacing Alestes nurse.
Mormyridae: a phenomenal failure of most species of this family is recorded in the lake.

The formation of Lake Volta has led to the success of Cichlidae, Anabantidae and Centropomidae, while Mormyridae, Characidae and Schilbeidae have declined.

[A preliminary but significant report on the effect of the creation of Lake Volta on the fishes of Volta River. Family Cichlidae has responded most favorably to lacustrine conditions while the important family Mormyridae--for unknown reasons--has declined. The report has very useful "catch data" from various localities all over Lake Volta.]

Petr, T. 1967a. Fish population changes in the Volta Lake in Ghana during its first sixteen months. Hydrobiologia, 30(2):193-220.

The following changes in fish fauna of the newly formed Lake Volta were observed between 1965 and 1966.

Characidae: In rivers Black Volta as well as the Niger, characid fishes are recorded in low numbers in the dry season and high numbers in the wet. In 1965 a great increase of characids was recorded at Akosombo and Kpandu in the dry season (more than 1/2 the total catch of characids was recorded). But in the following dry season, the catch of characids at both stations went down while remaining high at Kete Krachi. Most of the changes recorded were due to Alestes spp. (particularly Alestes nurse), while the predatory Hepsetus and Hydrocynus remained relatively unchanged. The entomophagous Alestes spp. were feeding mostly on terrestrial insects, but showed some changes in diet; whenever the pelagic fishes, e.g., the clupeids became abundant, Alestes fed on these. Similarly, whenever the terrestrial insects were low, these fishes fed on aquatic insects or even plankton.

Cichlidae: In Black Volta River the catch of the cichlids never increased above 0.32% of the total catch. Although in the initial phase of lacustrinization they remained low. The following August, 1965, the cichlid catches increased drastically at Akosombo, Kpandu and Ampem; at several stations they now represent over 65% of the total catch. The most abundant cichlids are Tilapia galilaea and Tilapia nilotica; both of these species are algae or detritus feeders. The predatory Hemichromis spp. and Pelmatochromis have also shown increase; Pelmatochromis is insectivorous while Hemichromis spp. feed on insects and small fishes.

Mormyridae: The mormyrids are the commonest and most abundant species in Black Volta River in the dry season. During high water, they carry out breeding migrations. The formation of the lake led to the disappearance of the mormyrids in most of the lake. Since the biomass of insects in the lake has increased manyfold, food does not seem to be a limiting factor. The mormyrids, however, prefer well-oxygenated waters and riverine rocky habitats for breeding. In the initial stages of its formation, Lake Volta became largely anoxic and the rocky habitats were drowned. This may account for the decline of the mormyrids.

Cyprinidae: In the riverine habitat, the abundance of the cyprinids varies a great deal in the wet and dry season because they migrate at high water. In Lake Volta, they increased at the beginning, but in the subsequent wet season they declined. It is possible that this "decline" was due to a migratory movement. Labeo spp. are the commonest cyprinids in the lake--particularly in the south. They feed on detritus, aufwuchs, and mud.

(Petr, 1967a, continued)

Citharinidae: The citharinids are not very common in the river or the lake except Distichodus rostratus and Citharinus distichoides have increased somewhat at some stations in the lake. Distichodus feeds on macrophytes--although when phytoplankton blooms, it may feed on this; the increase of Distichodus is probably due to the increase of phytoplankton as well as that of subaquatic macrophytes, e.g., Ceratophyllum. Citharinus spp. feed on mud, plant detritus and aufwuchs.

Centropomidae: Lates niloticus has increased considerably in the lake--presumably owing to the creation of weed beds that it uses for reproduction as well as the increase of prey species of fish (e.g., cichlids, clupeids, and schilbeids).

Mochocidae: A number of specialized species of Synodontis live in Lake Volta but their identification is difficult. As a whole the mochocids have declined in the south of the lake while maintaining their initial numbers in the north. Synodontis membranaceous feeds on benthic algae and bottom mud, but other species feed on chironomid larvae, etc.

Schilbeidae: Three schilbeids, Schilbe mystus, Eutropius niloticus, and Physailia pellucida are found in the lake. Although Schilbe mystus has increased at Kete Krachi and Physailia pellucida has become quite abundant in the south, the schilbeids have not succeeded remarkably in the lake. Schilbe and Eutropius feed on insects and fish, but the pelagic Physailia feeds on chironomid larvae. It undergoes vertical migration diurnally--apparently responding to the timing of emergence of the chironomids.

Bagridae: The abundance of the bagrids has not changed very much in the lake except in the south where Chrysichthys replaced Alestes nurse as the most abundant species at Akosombo in 1965. Chrysichthys is insectivorous while Bagrus spp. feed on insects and fish.

Clariidae: The clariids of Lake Volta include Clarias spp. and Heterobranchus spp.; Clarias spp. occur all year (particularly C. angullaris which is omnivorous).

Other fish families of Volta River show the following tendencies in the lake: Malapturidae (not recorded in the lake); Osteoglossidae (Heterotis niloticus has increased in the lake); Anabantidae (Ctenopoma has increased in the lake); Ophiocephalidae (occasional specimens recorded), while Gymnarchidae, Tetraodonlidae and Polypteridae remain rare in the lake.

Following is an outline of food and feeding regimes of fishes.

Plankton: The commonest plankton spp. include Peridinium, Volvox, Melosira, Fragillaria and Microcystis. The obligatory planktivores are Tilapia galilaea, T. nilotica. The facultative planktivores are T. zillii, T. guineensis(?), Distichodus, Citharinus, Labeo, Alestes, Synodontis and Clarias.

Macrophytes and aufwuchs: The commonest plants eaten are Ceratophyllum, other aquatic weeds, and the periphyton (aufwuchs) growing on them. Obligatory macrophytophagous species are T. zillii, T. guineensis, Distichodus rostratus and D. engycephalus. Facultative macrophytophagous species are Ctenopoma, Chrysichthys and Synodontis spp.

Mudsuckers: The following species all use bottom mud as food periodically: Labeo senegalensis, L. coubie, Citharinus citharus, T. zillii, T. guineensis, Distichodus, Claria and Synodontis.

Invertebrates: Terrestrial and aquatic insects, zooplankton: Ctenopoma, Auchenoglanis, Hemichromis, Chrysichthys, Synodontis, Alestes, Polypterus, Protopterus, etc.

Piscivores: Obligatory piscivores include Lates, Hydrocynus, Hepsetus. Facultative piscivores include Clarias, Hemichromis, Eutropius, Alestes, Schilbe, Ophiocephalus, Bagrus, Polypterus.

Omnivorous: The omnivorous species are Heterotis and Clarias.

The majority of abundant species of fishes in River Volta were benthic invertebrate feeders. In the dry season the mormyrids were the most common species while in the wet season Alestes and some schilbeids became dominant. Following the creation of the lake the mormyrids have nearly disappeared while a number of herbivorous (planktivorous as well as macrophytophagous) species have become very abundant. This is particularly reflected in the dramatic rise of the herbivorous cichlids--particularly in the south. A number of invertebrate feeders have also increased by utilizing the rich invertebrate fauna associated with the periphyton which developed on the submerged trees.

Lake Volta is compared with Lake Kariba as follows: (1) in both lakes plankton-feeding species have increased. (2) Whereas Lake Kariba is dominated by planktivores, Volta is dominated by insectivores. (3) Mudsuckers increased in Kariba while they have decreased in Volta. (4) The shallowness and periodic overturn of Volta will favor the development of a benthic as well as shore invertebrates. Fishes feeding on them will remain important.

Finally, the reasons for the disappearance of mormyrids in Volta are discussed.

Petr, T. 1967b. International symposium on man-made lakes (2-24 November, 1966 in Accra, Ghana). Hydrobiologia, 30(3/4):600-604.

A summary of papers delivered at the Accra Symposium on Man-Made Lakes; three papers on Lake Volta fishes are mentioned. It is noted that since the formation of the lake, the cichlid and clupeid fishes are increasing while the previously common mormyrids are declining.

Petr, T. 1967c. Food preferences of the commercial fishes of the Volta Lake. Volta Basin Research Project Tech. Rept., X 22. University of Ghana, 7 pp.

Describes the food of the 22 most important commercial fishes of Lake Volta in the early phase of its formation (Nov. 1964-1966). The food sources are as follows:

1. Macrophytes
2. Phytoplankton
3. Epiphytic aufwuchs
4. Zooplankton
5. Organic bottom mud
6. Aquatic insects
7. Terrestrial insects
8. Fish (and fish scales)

Prior to the formation of the lake, the majority of riverine fishes performed "lateral migration" into the surrounding inundated plains. These plains provided breeding sites for the adults and also food and protection for the alevins. The flooded Volta Basin created a permanent flood plain and unlike the situation in the rivers, the fishes do not have to return to the river following the floods. Because vast areas of the lake-bed were not cleared of vegetation, the lake became highly anoxic--particularly close to the bottom. This discouraged the formation of benthos, but the drowned trees provided much surface for the development of epiphytic diatoms and algae (periphyton). The trees and the periphyton on them led to the development of a very rich invertebrate fauna. Fishes readily shifted their feeding from the benthos to the insects on the drowned trees.

Schilbe mystus and Eutropius niloticus now feed on Povilla adusta (Ephemeroptera) which has developed on the tree surfaces all over the lake. The cichlids have greatly benefited by the formation of the lake. The macrophytophagous and the microphytophagous species of Tilapia have both increased just as the predominantly insectivorous Pelmatochromis and Hemichromis. The success of several species of pelagic fishes, e.g., Pellonulla and Physailia will favor the piscivorous Lates and also Hemichromis. Heterotis niloticus is increasing very rapidly--this is due to the increase of zooplankton in the lake.

Petr, T. 1968a. Distribution, abundance and food of commercial fish in the Black Volta and the Volta man-made lake in Ghana during its first period of filling (1964-1966). Hydrobiologia, 32(3-4):417-448.

A detailed study of the common mormyrid species of River Volta at Bui Gorge Area. Information includes feeding and breeding habits. The mormyrids are dominant fishes in the river, but have disappeared from the lake. The report concludes that food cannot be the limiting factor for the mormyrids in the lake since a rich insect fauna has developed in the lake. Two possible reasons for their disappearance might be: (1) the anoxia of much of Lake Volta in its initial stage; (2) the disappearance of riverine rocky habitats which the mormyrids use for breeding.

[Valuable data on the ecology of the following riverine mormyrids is given: Hyperopisus bebe Lacepede, 1803; Mormyrus rume, C & V, 1846; M. hasselquisti, C & V, 1846; M. macrophthalmus, Gunther, 1866; M. delicionsus, Leach, 1818; Gnathonemus tamandau, Gunther, 1862; G. senegalensis, Steindachner, 1870; G. pictus?; G. cyprinoides Linne, 1784; Petrocephalus bane, Lecepede, 1803.]

Petr, T. 1968b. Population changes in aquatic invertebrates living on two water plants in a tropical man-made lake. Hydrobiologia, 32(3-4):449-485.

Between February and November 1965 two aquatic macrophytes, Pistia stratiotes L. (floating) and Ceratophyllum demersum L. (submerged) have increased substantially in the littoral of Lake Volta. Many invertebrates use these plants as substrate and as a source of food (they either feed on the plant itself or on the periphyton); the increase of Pistia and Ceratophyllum has led to a dramatic increase of such invertebrates (several of these are important vectors of human parasites). This investigation was carried out in the Gorge Region (Akosombo).

Ceratophyllum demersum: In the inshore region, rising water level, breakdown of stratification and greater transparency of water following June 1965 led to a rapid increase of this plant, which in July formed a strip 50-200 m wide which was visible on the surface. Between August and October much wave action uprooted the plant and by November it was found at a depth of 2 m. Chironomid larvae (with Chironomus fractilobus Kieffer in overwhelming dominance), odonata and zygoptera nymphs (particularly Pseudagrion sp.), crustacea and oligochaetes were recorded from the plant. The invertebrate fauna shows a resting phase (February-May), and expanding phase (June-August) and another resting phase (October-). During the flood (June-July) while the plant increased, the fauna was low but by August all invertebrates were increasing.

In the offshore region, Ceratophyllum appeared between February-April, and then disappeared. The invertebrate fauna on the offshore plants was much lower than recorded on the inshore plants. The offshore fauna was dominated by ephemeroptera nymphs and oligochaetes--the

(Petr, 1968b, continued)

chironomids were present in lower numbers. The lower invertebrate fauna here is due to the instability of the plant (due to waves) and heavier fish predation.

Pistia stratiotes: This floating weed was restricted to a strip 0.5-2 m wide in February-June. But in July it spread rapidly to form a mat 200-300 m long and 150 m wide. In August wind-action broke up the mat which disappeared in December. Between February and May, the abundance of invertebrates was low and dominated by dipteran larvae and odonata nymphs. During the flood (July), the fauna decreased but in August all invertebrates were increasing. By December, the invertebrates disappeared along with the plant.

The author presents a detailed list of taxonomic groups of invertebrates associated with Ceratophyllum and Pistia.

The aquatic weeds Ceratophyllum and Pistia are utilized as food by several Lake Volta fishes; the weeds are most important because they support a rich epiphytic fauna utilized by many invertebrates. The latter are also utilized as food by many fishes. A few invertebrates of Lake Volta are medically important.

The invertebrate fauna of each weed is distinct and shows a cyclic behavior just as the weed (particularly Ceratophyllum) itself does.

Petr, T. 1968c. Problems of assessment of periphyton production in a tropical man-made lake. Rept. Regional Meeting of Hydrobiology in Tropical Africa. Makerere Univ. College, Kampala, Uganda (20-28 May, 1968), UNESCO Reg. Cent. for Sci. Tech. for Africa, pp. 144-145.

In Lake Volta the initial deoxygenation of the hypolimnion has prevented the formation of much benthos. The drowned trees along its shoreline support a very rich periphyton which in turn allows the development of a rich invertebrate community associated with it. The most successful invertebrate on the submerged vegetation is Povilla adusta (Ephemeroptera) which is being increasingly utilized by insectivorous fishes. Of all the invertebrates living in the lake, Povilla has the highest biomass. Some of the fishes now actively utilizing this source of food are: Alestes, Eutropius, Pellonula, Physailia.

Petr, T. 1968d. The establishment of lacustrine fish population in the Volta Lake in Ghana during 1964-1966. Bull. de l'I.F.A.N., Tome XXX, Ser A, 1:257-269.

In the earlier phase of the formation of Lake Volta, a mass mortality of Chrysichthys occurred--presumably due to the deoxygenation of water following the development of an algal bloom.

During this phase fish catches were dominated by Alestes, Chrysichthys, Hydrocynus, Lates, and Labeo. A few months following damming the schilbeid Physailia and the clupeid Microthrissa both appeared as pelagic species; these species were almost unknown in the river. By the end of the first year (May 1965), Alestes nurse was the most common species followed by Labeo, Distichodus and Lates. This was essentially the high season pattern of abundance in the river prior to damming. By May 1965 a radical change in the fish fauna was evident in the great increase of cichlids in the southern stations; by October 1965 the cichlids formed 3/4 of the total catch of Kpandu, Ampem, and Akosombo. The mormyrids which formed 68% of the total dry season catch in the river almost disappeared in the lake.

At the end of its first year, Lake Volta has a typically lacustrine fish fauna (dominated by the cichlids and clupeids) while north of Yeji the fauna was still riverine (dominated by the characids). During lacustrinization, the herbivorous and insectivorous fishes have enjoyed great success. As the bottom water gets more oxygenated bottom feeders will also benefit. Similarly, the increase of pelagic characids and clupeids will help the predatory Lates and Hydrocynus. Perhaps the fastest growing species in the lake is Heterotis niloticus--a zooplankton feeder.

Petr, T. 1969a. Fish population changes in the Volta Lake over the period January 1965 - September 1966. In Man-Made Lakes, The Accra Symposium, ed. L. E. Obeng, pp. 220-234. Accra: Ghana University Press.

No fish-fauna surveys were carried out in Volta River prior to damming. This report summarizes changes in the fish fauna of Volta Lake during filling and compares the fauna with that found in Black Volta River at Bui Gorge upstream.

Inundation of the Volta basin led to the near disappearance of the mormyrids--possibly due to the elimination of rocky spawning sites. Some characid species, e.g., Alestes, performed irreversible migrations and have declined in the lake. However, the cichlids have increased enormously at most stations. Increases have also been noted in Lates, Hydrocyon, Hepsetus, Cynothrissa, and Pellonula. In 1965-1966 as Alestes became rare at Akosombo; Chrysicthys increased.

Petr, T. 1969b. Regional meeting of hydrobiologists of tropical Africa (20-24 May, 1968 in Kampala, Uganda). Hydrobiologia, 33(3-4): 507-512.

[A report of the proceedings of the meeting.]

Petr, T. 1969c. On the preference of some aquatic insects for hard or softwood trees. Volta Basin Research Project Tech. Rept., X 33 2 p.

Since much of Volta basin was not cleared of vegetation prior to damming, the lake has a very large number of drowned trees. Tree surfaces have been colonized by a number of invertebrates which feed on the periphyton. The invertebrate fauna of the tree surfaces is very important because the formation of benthos has been retarded by the early deoxygenation of the lake water. Povilla adusta (Ephemeroptera) is the commonest inhabitant of tree surfaces except where wave action is strong; in latter areas, trichopterans (Amphipsyche and Ecnomus) predominate.

This investigation is about the ability of various invertebrates to colonize hardwood (at Adudzega) and softwood (Afram-Pawmpawm confluence). Trichopterans comprise 99% of the biomass on the hardwood trees. Amphipsyche is dominant, followed by Ecnomus. Povilla adusta forms 99% of the biomass on the softwood trees. Inability of Povilla to colonize hardwood trees is due to its inability to burrow through hardwood. The Trichoptera do not burrow into wood.

Petr, T. 1969d. Development of bottom fauna in the man-made Volta Lake in Ghana. Verh. Internat. Verein. Limnol., 17:273-282.

During circulation the benthos in Lake Volta reaches deep into the lake, but abundance is low. In the northern (riverine) basin benthos is found at the bottom mostly and is evenly distributed. During stratification the benthos also stratifies and is found in great concentration. The biomass of the benthos is maximum during stratification and minimum during mixing.

The chief benthic organisms are chironomids (59% of the total biomass) and Povilla (30.2%). In the littoral region, wherever Pistia and Ceratophyllum occur, there are many Bulinus spp. gastropods. In certain localities the benthos is dominated by Ecnomus and Dipseudopsis. Between 1966-1968, Povilla has colonized the entire lake. It buries itself in the submerged trees during daytime and emerges at night to feed on periphyton. The increase of Povilla has led to a change in the diets of many insect-feeding fishes. These now feed overwhelmingly on Povilla whereas previously they had broader spectra of diet. In the north Alestes, Eutropius and Schilbe--all of which utilize Povilla--have become the dominant species.

As the lake matured, the biomass of benthos has decreased. But considering that insects in the tropics produce many generations in a single year, the productivity must be high.

Petr, T. 1970a. Microinvertebrates of flooded trees in the man-made Volta Lake (Ghana) with special reference to the burrowing mayfly Povilla adusta Navas. Hydrobiologia, 36(3-4):373-398.

Great increase of periphyton is noted in Lake Volta. It is an important food for some fishes; most of it is utilized by larvae or nymphs of numerous aquatic invertebrates which have increased vastly in the lake.

Invertebrate species	Number %	Standing Crop %
Povilla adusta	74.95	90.42
Amphipsyche	8.50	6.36
Chironomids	4.78	1.17
Ecnomus	5.02	1.06

High density of these organisms exists in the south (Ampem), decreasing to the north (Yeji). The south has 30 times the number of organisms found in the north; in terms of biomass the south is 13 times richer than the north. At all stations except Kpandu (where Amphipsyche is dominant) Povilla is the most abundant organism. Most organisms decrease with depth. The effect of oxygen and wave action on the distribution of various species is discussed and the ecology of Povilla adusta is presented.

Petr, T. 1970b. The bottom fauna of the rapids of the Black Volta River in Ghana. Hydrobiologia, 36(3-4):399-418.

Increase in the biomass of invertebrate fauna in Black Volta River is related to increased water flow. The increases are mainly due to the increase of the web spinning Cheumatopsyche larvae. Higher current of water also increases food supply of this species. At the end of the dry season, highest biomass of benthos is achieved; flood affects their density adversely.

Most invertebrates living in the river would be destroyed in lacustrine conditions except larvae of Ecnomus and Cricotopus which may live in the lake wherever riverine conditions persist. Exposed surface of flooded trees and increased wave action will allow Ecnomus and Cricotopus to persist in a lake, e.g., Lake Volta.

Petr, T. 1970c. Chironomidae (Diptera) from light catches on the man-made Volta Lake in Ghana. Hydrobiologia, 35(3-4):449-468.

A list of chironomid species is provided for the Volta Lake in Ghana, a man-made lake in tropical West Africa which started to fill in 1964. Insects were attracted to lights on the research vessel "Tilapia" at six different stations from 1966 to 1968. From the 25,128 specimens collected, 45 species were identified. Twenty-one

(Petr, 1970c, continued)

species are recorded for the first time in Ghana. The most abundant are: Nilodorum fractilobus, Chironomus formosipennis and Nilodorum brevibucca. The larger number of species occurring in the transitional river-lake zone, compared with the lake itself, is discussed in relation to the changes in the environment during each year as a result of the alternating dry and rainy seasons.

Petr, T., and J. D. Reynolds. 1969. Fish population changes in the Volta Lake in 1968. Volta Basin Research Project Tech. Rept., x 32, University of Ghana, 3 pp.

In 1968 Lake Volta rose 2 m. This survey shows that in the southern basin (Ampem, Pawmpawm, Lomnava, Aveme and Aglama) cichlids form 80.98% of the total catch (Tilapia galilaea is the dominant cichlid). Cichlids are also gaining ground in the north (at Yeji 40.88% of the catch is due to T. galilaea alone); however, in the river section the cichlids form only 12% of the total catch.

In 1968 the characids have dropped in numbers from previous years. Alestes macrolepidotus remains dominant but other species of this genus have declined. A. baremose has been replaced by Eutropius niloticus. The change in the characid population may be due to migrations in the flood.

Other species mentioned are: (1) The migratory Labeo coubie, which increased at Yeji and Kete Krachi in the flood. (2) Citharinus citharus (no peak of this species at Kete Krachi in April-May as recorded in 1967, but at Yeji the peak occurred again). (3) Lates niloticus appeared to be succeeding in the lake, as many young of this species were caught at Yeji. (4) Synodontis spp. were dominant in the north; several species were caught. (5) Cynothrissa showed a dramatic increase at Yeji (from 39-70% of the catch); it is more successful in the north because it needs a riverine environment to breed. (6) Mormyridae remained restricted as before.

Pierce, P. C. 1971a. A comparative evaluation of fish catch and economics for multifilament and monofilament gill nets at Volta Lake. USAID Volta Lake Technical Assistance Project Report (641-11-190-028), 31 pp.

Two nets each of 102, 127 and 178 mm stretched measure nylon multifilament and monofilament webbing, and two nets of 229 mm stretched measure monofilament webbing were tested at Volta Lake during an eight-month period in 1969 and their catch data compared. During this study the 14 test nets took 19 species totaling 1,332 fish weighing 1,829.3 kg. Tilapia spp. dominated the catch for the 102 and 127 mm gill nets, and Lates niloticus comprised most of the 178 and 229 mm nets catch by weight. Eleven percent of the total catch consisted of species of poor or no economic value. Monofilament nets took 3, 5 and 7 times as much fish by weight as did their multifilament counterparts for mesh sizes 102, 127, and 178

mm respectively. Of these three mesh sizes, monofilament webbing was the most economic and proved potentially more profitable as mesh and twine sizes increased. No multifilament gill net tested paid for itself during the study period; however, the 127 mm mesh should have within the life of the net.

The catch superiority of the monofilament gill nets was found to be due primarily to this webbing material's lower visibility in Lake Volta's relatively clear water. The 229 mm mesh monofilament flat net (mono=) was the most economical gill net tested, followed by the 178 mm (mono=), 127 mm (mono=) and the 229 mm (sunken mono+) mesh sizes. The 178 mm mesh floating monofilament gill net (mono+) was the only net tested that proved highly selective in catching Heterotis niloticus, a species of low commercial value at Lake Volta.

Study period: January-October 1969.

Pierce, P.C. 1971b. Aquatic weed development, impact and control at Volta Lake, 1967-1971. USAID Volta Lake Technical Assistance Project Rept. (641-11-190-028), 89 pp.

Data collected during a four-year study (1967-1971) at Volta Lake showed that aquatic weed abundance and distribution changed during the early lake fill period (1964-1968).

Prior to 1968, the lake's plant community was dominated by floating Pistia stratiotes, Lemna sp., Salvinia nymphellula, and Scirpus cubensis. Floating "grass" islands were often created when Scirpus cubensis colonized thick mats of Pistia. After 1968, however, these floating weed species became less abundant, in general, and were restricted to sheltered, shallow coves and bays, or near confluences where major streams enter the lake. The latter was found to be particularly favorable for Pistia-Scirpus island development if large numbers of emergent dead trees were present to provide suitable anchorage to hold the weed beds in place.

After the lake fill in 1968, the water level fluctuated gradually, and many species of semi-aquatic plants became established on the exposed lake shore during the drawdown period (December-June). Some of these species, particularly Vossia cuspidata and Polygonum senegalense, were found to be tolerant of flooding to a depth of three vertical meters--the usual annual range of water fluctuation. The former species spread rapidly, and by 1971, it had infested mucl of the lake's shallow shoreline--especially along the western side of the reservoir. Polygonum was found to be more abundant in the more protected coves and bays. Also in those areas, Alternanthera sessilis was common, but it did not appear to be well suited to

(Pierce, 1971b, continued)

prolonged deep flooding; and therefore, it was seldom seen during the latter part of each flood season. These marginal weed beds, in addition to submerged weeds consisting mainly of Ceratophyllum demersum, were found to support large populations of snails, vector carriers of human Schistosomiasis (Bilharziasis). In an effort to find an effective means of combatting this waterborne disease, studies were conducted at Volta Lake to determine if by reducing aquatic weeds and shoreline debris--a known preferred habitat for these snails--the snail population could also be reduced to below normal transmission levels. In May 1969, a three-hectare shoreline area at Ampem was cleared of all standing vegetation and sprayed with fenac and diuron at rates of 17 and 4 kilograms equivalent per hectare, respectively. No weed growth became established in the water throughout the test plot during the first year.

Pre-treatment snail surveys showed that the snail population was fairly evenly distributed along the entire shoreline within one kilometer of Ampem. However, after the treatment was made, and the test site was flooded during the following lake fill period, snail surveys produced only one snail along the test plot's 260 m of weed-free shoreline--compared to 98 Bulinus truncatus and 112 Bulinus forskali snails collected along a comparable length of weed-infested shoreline located outside of the cleared area. Four snail surveys conducted during the second year (1970-71) produced a total of 21 snails within the cleared area. Most of these, however, were collected in a partially sunken fishing canoe and therefore should not have been included in the count. At the same time, 201 snails were collected in the uncleared area. Therefore, it was concluded that localized aquatic weed and debris control could be an effective method for reducing snail populations at Volta Lake.

Other aquatic weed control tests using 12 different herbicides and their combinations showed paraquat to be effective for the control of floating islands of Pistia-Scirpus. A spray mixture containing one part paraquat and 200 parts of water (equivalent to 2.5 l/ha) was sprayed over the weed bed until the vegetation was thoroughly wetted. Poor results were noted, however, when paraquat (.33 ppm), 2, 4-D granules (200 kg/ha) and diuron granules (100 kg/ha) were applied for the control of submerged Ceratophyllum. Also, poor results were obtained when mature Polygonum, either in or out of the water, was sprayed with paraquat (1 to 200 spray mixture) or 2, 4-D amine liquid (1 to 50 spray mixture). However, these same concentrations were found to be totally effective for controlling young plants of all species (except 2, 4-D used on grass species) growing on the exposed lake shore during drawdown. Data collected using other herbicides showed that they too were generally effective for the control of young plant species, but not for mature growth.

Clearing fishing strips, for setting gill nets in flooded weed beds, was successfully demonstrated using a combination of pre-flood cutting, burning, and post-flood wading and weeding. Where Polygonum and Alternanthera were the problem, only pre-flood cutting and burning were necessary. However, where Vossia was encountered, post-flood weeding was required also.

Ecological studies conducted at Volta Lake indicated that Polygonum supported large quantities of fish food organisms--particularly the mayfly Povilla adusta whose larvae readily burrow into Polygonum's hollow stems. Forty-two linear meters of randomly sampled hollow Polygonum stems produced 448 Polygonum larvae, for an average of 11.6 larvae per linear meter. Few signs of these larvae occupying the hollow stems of Vossia were noted.

Further studies showed that Povilla larvae are readily eaten by a wide variety of fish species at Volta Lake. During an estimated 10 man-hours of fishing using these larvae for bait on small fish hooks, 16 species of fish were taken. These findings clearly indicated that Polygonum beds are beneficial to the lake's fishery. However, observations made during 1971 showed that the flooded Polygonum beds were reduced considerably compared to previous years, and that this reduction was attributed to the damage the burrowing larvae produced in the plants.

Other forms of natural biological control that were either seen or suspected to have occurred at Volta Lake during the study are discussed.

Pierce, P.C., and A. Opaku. 1970. Summary of aquatic weed survey and control data for Volta Lake during 1969. 3rd Ann. Meet. National Weed Comm. for Ghana (C.S.I.R.), Accra, Ghana (Cyclostyled), 10 pp.

Between 1964-1967, Lake Volta was infested by the following floating or submerged water weeds: Pistia, Scirpus, Cyperus, Ceratophyllum and Utricularia. In 1968 marginal rooted aquatic weeds were on the increase; the latter weeds may in the long run pose more serious problems than the former. The new infestation includes Vossia, Polygonum, Alternanthera, and Ludwigia.

In limited numbers the weeds are beneficial to fishes--providing food and shelter for many species. But the uncontrolled development of Vossia etc. on the banks poses serious problems for the present fishery. The vegetation also supports sizeable populations of aquatic invertebrates which act as vectors of bilharzia and other diseases of man.

Experimental control of the weeds is described.

Proszynska, M. 1966. A quantitative study of the Cladocera and Copepoda in the Volta Lake. Volta Basin Research Project Tech. Rept., X 10. University of Ghana, 3 pp.

A preliminary report on the planktonic crustaceans (Cladocera and Copepoda) at Ajena Station, Afram Confluence and Volta River (below the dam); observations were made between May 1964 and December 1965. The genera mentioned are: (1) Cladocera--Diaphanosoma, Ceriodaphnia, Bosmina, Moina; (2) Copepoda--Cyclops.

A very unpredictable picture of distribution and quantity is reported at all stations. Immediately following the closure of the dam, planktonic crustaceans were found through the water column (10 m deep). However, in 1965 most species were restricted to the upper layer of the water. Sudden disappearance of the planktonic crustacea is attributed to "mass mortalities" the causes of which are not presented. A mass mortality of zooplankton and fishes was recorded in July 1964; the author suggests that the fishes perished because of the disappearance of zooplankton.

Only adult crustaceans were found at Ajena Station; the author suggests that the origin and growth of most species occurs elsewhere in the lake--perhaps at Afram confluence and other such sites.

[A highly preliminary and qualitative report (without a complete list of species of planktonic crustacea). It is dubious that the fish mortality observed was caused by the crash of zooplankton population. Mass mortalities which commonly occur in all the major African lakes are associated with local "overturns" or "seiche" movements which reduce oxygen in the water. Presumably the aerobic zooplankton also disappear for the same reason. Conclusions about the so-called "mass mortalities" of zooplankton can only be made when we know more about the limnology of the lake. Also, the role of annual flooding, as well as temperature, needs to be taken into account.

Proszynska, M. 1968. Bibliography of Cladocera and Copepoda of inland waters. Ghana Journ. Sci., 7(1-2):37-49.

[A thorough bibliography of Cladocera and Copepoda of African fresh waters. Includes papers from 1845-1964.]

Proszynska, M. 1969. A preliminary report on the quantitative study of the Cladocera and Copepoda in the Volta Lake, 1964-1965. In Man-Made Lakes, The Accra Symposium, ed. L. E. Obeng, pp. 127-132. Accra: Ghana University Press.

Following closure of the dam (1964), zooplankton was distributed throughout the water column. In 1965, it was concentrated in the top 5 m--particularly between 2-5 m. A repeated crash of the populations was observed; the disappearance is related to the annual

flood season. Evidence indicates that much of the zooplankton does not develop in situ but comes from other localities, e.g., the Afram confluence.

Rajagopal, P. K. 1969. Preliminary observations on the vertical distribution of plankton in different areas of the Volta Lake. In Man-Made Lakes, The Accra Symposium, et. L. E. Obeng, pp. 123-126. Accra: Ghana University Press.

The plankton of the southern basin is poorer in quality and quantity compared to the northern basin of Lake Volta. However, in the shallow water areas of the south very high densities of plankton are recorded.

Zooplankton: Ciliates and rotifers (Filinia) are dominant in composition; crustacean plankton is sparse.

Phytoplankton: Of the stations studied, Ampem is richest in phytoplankton. Ampem also appears to be an area where resident zooplankton multiplies.

Ram, J. 1968. Eyes on the Volta Lake. New Scient., 39:540-541.

A very general note on the events in Lake Volta following damming.

[The report is of no scientific value.]

Regier, H. A. 1970. Report of travel to Lake Volta (Ghana) and Lake Kainji (Nigeria) Fisheries Research Projects, from 15 November to 3 December 1970. FAO Fisheries Travel Rept. and Aide Mem., No. 376, 2 pp.

Narrative report of a trip to Lakes Volta and Kainji to start analysis of fish stock assessment problems in these lakes.

Reynolds, J. D. 1966. The clupeids of Lake Volta and their possible exploitation. Volta Basin Research Project Tech. Rept., X 15. University of Ghana, 6 pp.

Two closely related clupeid species, Cynothrissa mento and Microthrissa miri, live in Lake Volta; their characteristics are as follows: (1) Cynothrissa mento--This is the larger of the two species (150 mm; 40 gm); and it is predominantly piscivorous. In the early part of the lake's history it was mainly caught near Kete Krachi and Yeji. Breeding season: ? (2) Microthrissa miri--a smaller species (80 mm, 3 gm) is caught all over the lake; it is insectivorous and probably also feeds on scales of other fishes. Breeding season: July, August.

(Reynolds, 1966, continued)

These clupeids exhibit a diurnal vertical migration that is probably associated with the emergence of aquatic insects in the evening. At this time, the fishes form shoals which later disperse on the surface of the lake. At dawn, the shoals re-form and disappear into deeper waters.

Very little is known about the breeding biology of the species except that they probably attach their eggs to a substrate in shallow water areas. It is noted that these clupeids do not migrate into the flooded areas during high water season; survival of the stock is therefore probably assured by some mechanism protecting the young from the predators.

The occurrence of periodic large shoals is associated with limnological conditions in the lake. Earlier in the paper a very brief account of freshwater clupeids of Africa is given.

Local methods of fishing are presented and a case is made against the introduction of non-indigenous clupeids into Lake Volta. The ecological status of Lake Volta clupeids is presented. There are also comments on the commercial aspects of the clupeid fishery.

[A good introduction to the biology of Lake Volta clupeids.]

Reynolds, J. D. 1967. Notes on juveniles of commercial fish attracted to light on the Volta Lake, 1966-1967. Volta Basin Research Project Tech. Rept., X 21. University of Ghana, 15 pp.

Analysis of young pelagic fish caught by "light fishing" method at night; the fishes examined only include the commercially important species. In the riverine northern section of the lake about 22 species (10% of these are pelagic) are recorded while in the south, all of the 5 common species are pelagic. This work does not concern the small, unexploited pelagic species Pellonula afzeliusi, Physailia pellucida and Cynothrissa mento; for some of the fishes examined "condition factor" (K) and "fecundity coefficient" (f) are calculated.

Centropomidae: Lates niloticus (Linne, 1762) has established a breeding population in the lake; this has been probably facilitated by the development of areas of subaquatic vegetation on the shores. The catch has increased from 1% or less in the river to about 10% in the southern part of the lake. The breeding season in the lake is probably from December to January, and it is possible that the season has been extended in the stable lacustrine environment.

Cichlidae: In Black Volta River, cichlids represent only 1% of the total catch of fish, but in the lake, they have increased up to 75% of the total catch at some stations. In this survey very few young specimens of cichlids were caught; they include: Tilapia zillii (Gervais, 1848), T. galilaea (Artedi, 1757); Hemichromis fasciatus (Peters, 1857), and H. bimaculatus (Gill, 1862). Of these, T. galilaea was found to be the most abundant species at some stations. The stomach contents of H. bimaculatus include insect larvae and zooplankton.

Schilbeidae: Schilbe mystus (Linne, 1762) was caught only at Yeji. Although it can breed in the lake, it lives only in the shallow water close to the shores. It spawns in high water during June and July. Its food includes Povilla adusta and other insect larvae as well as fishes. Eutropius niloticus (Ruppell, 1829) was caught at most stations, but seems to be most prevalent in the northwest. In the riverine habitat, it lives deep in the water and does not migrate into the flood plain to breed; it spawns in June and July. In the lake its breeding season is more drawn out and it also grows faster. Stomach contents include aufwuchs, insect larvae and beetles.

Bagridae: Chrysichthys auratus (Pellegrin, 1909) migrates in the river and reproduces during the rainy season. Although it is uncommon in the lake, it does reproduce there and most probably has an extended breeding season. C. nigrodigitatus (Lacepede, 1803) is more common than the previous species and has been caught at most stations. It breeds between June and October, i.e., during and after the rainy season. Its food includes benthic insects, terrestrial insects, zooplankton and fish. Bagrus bayad (Forskal, 1775)--only one specimen was recorded at Yeji; it was probably spawned in June at the beginning of the flood season.

Mochocidae: Only one specimen of Synodontis eupterus (Boulenger, 1901) was recorded at Yeji; it probably reproduces during the high water season. S. Gambiensis (Gunther, 1864) is the commonest species of this genus in commercial catch--chiefly in the northwestern part of the lake. In the river it spawns just prior to the floods, but in the lake it spawns during the floods (July to August).

Characidae: All riverine species of Alestes migrate into the flood plain during the flood to breed and utilize a new and abundant source of food. When flood waters recede, they return into the main stream. A. dentex sethente (Curvier et Valenciennes, 1849) is less common than A. barmose in the Volta basin. It probably spawns following the flood. A. baremose (Joannis, 1835) was frequently caught at various stations. In the river it breeds at the end of the flood season only, but in the lake it has several successive spawnings. Stomach contents revealed insects, grass seeds, blue-green algae and zooplankton. A.

(Reynolds, 1967, continued)

macrolepidotus (Cuvier and Valenciennes, 1869), although common in the lake, was not caught in the juvenile stage. It lives and feeds in the marginal shallows. In the lake, it probably enjoys an extended reproductive period. A nurse (Ruppell, 1832) in the rivers migrates up at the end of the flood season. In the lake, two successive spawnings have been recorded; the spawnings occurred at the start and middle of high water. Food consists of terrestrial and aquatic larvae and cassava scrapings. A. leuciscus (Gunther, 1867) is common in Lake Volta only in the riverine northwestern arm and reproduces at high water. Food consists of aquatic and terrestrial insects, cassava and grass seeds. A. imberi (Peters, 1852) was found in small numbers, but very little is known about its ecology.

Citharinidae: Distichodus engycephalus (Gunther, 1864) is common only in the riverine section of the lake. Its food consists of seeds, pieces of wood, detritus and aufwuchs. D. rostratus (Gunther, 1864) reproduces in the river at the start of the flood and the young later migrate into the flood plain. In the lake it frequents the shallow flooded areas.

Cyprinidae: Labeo senegalensis (Cuvier and Valenciennes, 1842) frequents the rocky habitats in the river; it is very rare in the lake--presumably because its habitat has changed in the lacustrine environment. But there is evidence suggesting successive spawnings in the lake. L. coubie (Ruppell, 1832) is more common in the lake than L. senegalensis. In the rivers it reproduces over an extended period at high water, but in Lake Volta it probably breeds at the end of the rainy season. Food consists of aufwuchs and zooplankton.

The northern riverine section of Lake Volta is dominated by a number of migratory species (Alestes spp., Labeo spp., etc.). Any attempts to initiate exploitation of pelagic fishes in this region will adversely affect the entire fishery of the region.

Reynolds, J. D. 1968. A bibliography of African fresh-water clupeids. Volta Basin Research Project Tech. Rept., X 24. University of Ghana, 6 pp.

[A thorough and very valuable bibliography of African freshwater clupeids.]

Reynolds, J. D. 1969a. Field key to commercial fishes of the Volta Lake. Volta Basin Research Project Tech. Rept., X 28. University of Ghana, 20 pp.

[A useful field key for Volta fishes.]

Reynolds, J. D. 1969b. The biology of the clupeids in the New Volta Lake. In Man-Made Lakes, The Accra Symposium, ed. L. E. Obeng, pp. 195-203. Accra: Ghana University Press.

About 20 species of clupeids have adapted themselves to estuarine or freshwater existence in Africa. They have undergone complex speciation and cannot readily be identified. In West Africa, the closely related species of Pellonula complex are found in rivers from Senegal to Niger. The Volta clupeids belong to this complex.

Cynothrissa mento (Regan (170 mm total length; 140 mm SL; 41 gm weight) has a long preorbital snout and massive jaws protruding in front. Pellonula afzeliusi (98 mm total length; 81 mm SL; 8.2 gm weight) has a less well-developed snout and lower jaw. Both are well-distributed in the lake, but Cynothrissa is more common in riverine areas (Yeji, Kete Krachi). They appear periodically in the Gorge Region; mass mortalities of clupeids have been recorded in this region periodically. These mortalities are caused by anoxia.

Migrations: Cynothrissa carries out longitudinal migration; diurnal vertical migrations accompanied by schooling are recorded for both the species. At 5:30 p.m. the fishes appear on the surface as shoals and later disperse to feed. At full moon they feed scattered and close to the surface. They move about in "feeding association" following schooling. At dawn shoals reform prior to disappearing into deeper water at 7:30 a.m.

Food and Predators: Pellonula feeds on aquatic and terrestrial insects mainly. It is an annual species whose population dynamics are controlled by predation. Cynothrissa is a predator and feeds on young Pellonula.

Reproduction: Pellonula breeds in July-September and perhaps again in December. It probably produces transparent pelagic eggs. Cynothrissa possibly does not spawn in the lake--preferring riverine habitats.

Reynolds, J. D. 1971a. Biology of the small pelagic fishes of the New Volta Lake in Ghana. II. Schooling and Migrations. Hydrobiologia, 38(1): 79-91.

Echo sounding suggests that the pelagic fishes appear on the surface between 1800-1930 hours. If the weather is calm they appear as a school and then disperse for feeding at 2-3 p.m. In choppy weather they remain at 3-6 m. During full moon they feed close to surface.

Surface observations showed that Pellonula and Physailia feed on emerging chironomids and Povilla between 1740-1845 hours (Yeji, Kete Krachi, Ampem). Larger groups were in deeper water. At Akosombo, these fishes remain on surface because of inclement conditions close to the dam. Here small groups were observed at 0730 hours, which later swelled to aggregations of 500-5,000 individuals.

(Reynolds, 1971a, continued)

Groups of pelagic species were also seen close to the shore in aufwuchs; however, well-defined and large schools are characteristic of open waters.

Cynothrissa , Barilius and Siluranodon most probably migrate into rivers in order to breed; Pellonula mostly breeds in the lake. These fishes also migrate against the wind--which explains their mortality close to the dam.

The development of pelagic habit in these fishes is discussed and it is suggested that schooling favors better utilization of food and escape from predation.

Reynolds, J. D. 1971b. A guide to the external sexing of some west African freshwater fishes. Ghana Jour. Sci., 11(1):3-11.

Methods of sexing West African freshwater fishes using external structural characters were investigated. Literature references to successful external sexing of Charcinidae were verified and Polypteridae and Clariidae appear also to be sexable. New methods to sex siluroid fishes, chiefly of the families Schilbeidae and Bagridae are described. In most cases the external character is not obvious before the fish reaches sexual maturity.

Reynolds, J. D., J. A. Adetunji, and H. O. Ankrah. 1969. Length-weight relationships of some Volta Lake fishes. Volta Basin Research Project Tech. Rept., X 29. University of Ghana, 12 pp.

Initial fish population studies in Lake Volta used fish lengths for stock assessment, etc. But future studies will be based on weight. This is a preliminary paper which tries to find a possible correlation between length and weight of the important commercial fishes of Volta.

Roberts, T. 1966. A preliminary report on the fishes of the Volta. Volta Basin Research Project Tech. Rept., X 9. University of Ghana.

Roberts, T. 1967. A provisional check-list of the fresh-water fishes of the Volta Basin, with notes on species of possible economic importance. Jour. West African Science Assoc., 12(10:10-18 (February).

A preliminary list of fishes of Lake Volta basin with brief notes on the taxonomic and ecological importance of some species.

Roman, B. 1966. Les poissons des hauts-basins de la Volta. Ann. Musee Roy. de l'Afrique Centrale in-80 (Zool.), 150:1-190.

Taylor, B. W. 1969. Volta Lake Research Project, further considerations of possible follow-ups. 3. Fisheries and Hydrobiology. Cyclostyled, 15 pp.

[Management aspects of freshwater fishery on Lake Volta.]

Taylor, G. T., and J. McAlister. 1969. A proposal for fisheries development at Kpandu Tokor, Volta Lake. Volta Lake Research Project Report. Cyclostyled. Ghana, 9 pp.

[A proposal of fishery development on Lake Volta with recommendations on the establishment of port and marketing facilities.]

Thys van den Audenaerde, D.F.E. 1968. An annotated bibliography of Tilapia (Pisces, Cichlidae). Musee Roy. de l'Afrique Centrale Document Zool., No. 14, Tervuren, Belgium, 405 pp.

Vanderpuye, C. J. 1971. Population of clupeids in Volta Lake. Lake Volta Research Project, Cyclostyled Report, 20 pp.

In addition to Cynothrissa mento and Pellonula afzeliusi, another clupeid, Sierranthrissa sp. is found in Lake Volta. Field experiments show that "light attraction" method of catching the clupeids is not very good because the fishes did not show much attraction to light. Length frequency distribution analyses exhibit 3 different modes in clupeid catches (32.3 mm; 47.5 mm and 87.5 mm). The second highest mode is attributed to Pellonula (50-60 mm) and the third to Cynothrissa (86-90 mm).

Experimental catch data dhow that the most effective mesh size for clupeid exploration is 13 mm (catches 97% in number and 86% in weight). This kind of net catch includes 90% Pellonula while the 25 mm mesh net catches include 90% Cynothrissa. Catch per round of fishes in Volta Lake includes 23% clupeids in weight.

Although the clupeids are believed to be mainly open-water species, maximum catch was obtained closer to shore (74% by number; 70% by weight in inshore areas). Like most other fishes, clupeids decline following the riany season. Some data on spawning are given.

Vanderpuye, C. J. 1972. Fishery resource assessment and monitoring in the development and control of fisheries in the Volta Lake. Volta Lake Research Project Cyclostyled Rept., 23 pp.

Direct estimation of fish stock in Lake Volta is not possible, making it necessary to use indirect methods. It is proposed that the fishery be expanded and utilization increased until changes become apparent. Evidence indicates that the lake is at present underfished.

This survey included experimental catching and rotenone treatment, and correlation with commercial catch in order to assess fish stock.

13-89 mm mesh nets: Less than 14% of the fishery utilizes these small mesh nets. These nets remove the clupeids which are at present not commercially utilized. The catch from this mesh size represented 73% of the total experimental catch.

102-203 mm mesh nets: Although in the commercial fishery the catch obtained by these nets consisted of 50% *Tilapia* spp., in the experimental catch only 15% was *Tilapia*. This difference is probably due to a difference in the areas fished. A fishing pressure index is prepared from this work.

Rotenone treatment: This procedure suggests that the standing crop varies from 1.2 kg/ha to 651.7 kg/ha (av. 170 kg/ha) in different localities. Although Bazigos estimated fish yield in Lake Volta to be between 42.90 kg/ha-45.14 kg/ha, this report suggests that higher yields can be obtained. It is estimated that the total catch in Lake Volta will stabilize at 39,000 tons annually in the future.

Viner, A. B. 1969. Observation of the hydrobiology of the Volta Lake, April 1965-April 1966. In Man-Made Lakes, The Accra Symposium, ed. L. E. Obeng, pp. 133-143. Accra: Ghana University Press.

Lake Volta has three layers of water during stratification. The top 5 m are well-oxygenated; between 5-20 m there is a considerable amount of gas, while below 20 m there is no oxygen during stratification. Sudden squalls only aerate the top layer, but a constant wind can cause much mixing even in the deeper water. Deeper water of the lake is more stable than the littoral zone.

Phytoplankton: At Ajena the phytoplankton is distributed throughout the water column. Elsewhere it shows stratification--being restricted largely to the epilimnion (particularly in the north). In the southern basin, the dominant phytoplankton is Bacillariophyceae; northwards, Myxophyceae and Chlorophyceae increase. The occurrence of these families is related to the stability-instability conditions in the lake. Under less stable conditions Bacillariophyceae have an advantage over the other families.

Estimates of primary productivity at various stations are given; it varies from 0.8 $gC/m^2/day$ at Afram to 5.2 $gC/m^2/day$. Areas with steady wind and consequently mixed waters have higher productivity than those in calm conditions.

Viner, A. B. 1970a. Hydrobiology of Lake Volta, Ghana. I. Stratification and circulation of water. Hydrobiologia, 35(2):209-229.

The climate and circulation of the lake are mainly under the influence of the Convergence Zone formed by southerly monsoons and northerly harmattan winds. The crucial agency of circulation is air movement rather than rainfall. Winds are even more important in the Gorge Region where much funnelling gives rise to instability of water.

Normally during daytime the water is stratified as follows: (1) 0-5 m shows significant diurnal variation; (2) 5-17 m shows slight variation; (3) 17 m and below, no variation. During the day, surface water warms up; photosynthesis, etc., increases the oxygen content of surface water. In the evening cool and dense water begins to sink into depths carrying oxygen with it. At night the daytime 5 m discontinuity breaks down and water down to 17 m is homothermal. But a discontinuity at 17-20 m remains during the night; this continuity is seen in oxygen (non below) and temperature (lower below). This situation reflects conditions in the Gorge Region and at Afram, Kpandu and Kete Krachi. Stability of the lake increases northwards as well as in the tributary entrances. However, at some shallow water stations, e.g., Ampem, complete mixing occurs periodically.

The Gorge Region undergoes irregular, complete or incomplete mixing. The instability is mainly caused by the southerly winds. There is the possibility that seiches occur in the gorge. Oxygen profiles suggest that density profile currents are a very important limnological feature of the lake. Complete deoxygenation can occur in the Gorge Region following an overturn; sustained wind action, however, can restore oxygen to a substantial portion of the water. The harmattan season is the period of maximum oxygenation (surface = 100% saturation; 15 m = 1% saturation).

Total solutes in Volta are low, but increasing (surface = 60-80 mg/L, bottom = 100-120 mg/L): conductivity at surface is 60μmho/cm and at the bottom is 80-100μmho/cm.

The complex morphometry is the chief cause of stability in Lake Volta; without it, the lake could circulate very often. The Gorge Region undergoes maximum mixing because of strong wind activity. Volta is a polymictic tropical lake.

Viner, A. B. 1970b. Hydrobiology of Lake Volta, Ghana. II. Some observations on biological features associated with the morphology and water stratification. Hydrobiologia, 35(2):230-248.

Zooplankton is found mainly in the epilimnion (except during circulation). The copepods show diurnal vertical migration.

Some evidence shows that population types of phytoplankton are related to morphometry. Flagellates, Volvocales, Desmidaceae and Dinophyceae do not exhibit much variation in various localities. However, Chlorococcales, Bacillariophyceae and Myxophyceae differ in various localities. North of Afram confluence, Bacillariophyceae increase; in some localities Chlorococcales are dominant over diatoms. Ampem and Afram show a rich variety of phytoplankton.

The euphotic zone at various localities in Lake Volta is as follows: Lake George - 3.5 m; Afram (Volta) - 4.5 m; Kpandu - 5.0 m; Kete Krachi - 5.0 m; and Yeji - 6.0 m. Primary productivity at various stations (measured as gm $O_2/m^2/day$) is estimated as follows: Afram - 1.2; Afram confluence - 0.3; Kpandu - 1.0; Yeji - 1.7; Ampem - 2.9-3.6.

Lake Volta falls within the "moderate" productivity category of Talling, 1965. Seventy percent of Volta water lies above 20 m discontinuity and is therefore productive.

Volta Basin Research Project. n.d. Control of aquatic weeds in the Volta Basin. Technical Report, XI, 5 pp.

The possibility of a weed problem on the Volta Lake is envisaged. The present situation is that though the main rivers of the Volta system are comparatively clean, there are a number of lagoons and backwaters rich in aquatic weeds. These could serve as a source of infection when the lake is formed. The total area of lagoons and backwaters in the area to be flooded in the first year is estimated at less than 2 sq miles of which only 100 acres is covered by weeds. The cost of a herbicidal chemical to destroy this quantity of weed would be between £200 and £400, according to the type of herbicide chosen.

It is therefore strongly recommended that at the end of this present dry season all the lagoons to be flooded by the following year are treated with chemical weed-killer. A relatively cheap operation at this stage would reduce the possibility of a much greater weed problem in the future.

White, E. 1969. Man-made lakes in tropical Africa and their biological potentialities. Biological Conservation, 1(3):219-224.

The creation of enormous man-made lakes offers to biologists the opportunity to develop new environmental resources and to plan their careful exploitation. However, the formulation of useful biological management plans is handicapped by the fact that, in all cases to date, insufficient research effort has been put into the pre-impoundment phase. Further, the inherent variability of each lake-site--in physiography, climatology, geology, hydrology, and bio-geography--makes prediction hazardous. Teams of research workers supported by national governments and the United Nations Development Programme are now established at most of the African man-made lakes. FAO usually implements the United Nations effort, and it is to this organization that we must look for coordination of the research effort, in the hope that this will lead to an early appreciation of the basic requirements for the biological management of these new resources.

Whitehead, V. 1969. Investigations into the food habits of some juvenile fish in the Volta Lake during the period October 1967 to March 1969, with some notes on distribution and abundance. Volta Lake Research Project Tech. Rept., X 30, 31 pp.

The general feeding patterns of the fish may be summarized as follows: Those having omnivorous diets and feeding both on benthic and surface fauna (i.e., Chrysicthys nigrodigitatus Alestes nurse, and Pelmatochromis guentheri); those feeding on benthic insects (Petrocephalus bovei, Gnathonemus senegalensis, Synodontis eupterus, S. nigrita); fish having carnivorous diets, feeding predominantly on surface insects and fishes (Eutropius niloticus, Schilbe mystus, and Lates niloticus); and fish having exclusively piscivorous diets (Hydrocynus sp., and Hemichromis fasciatus).

Bottom detritus, including benthic algae and plant debris were utilized as food by Tilapia galilaea, T. zilli, T. nilotica, Distichodus rostratus, D. engycephalus, and Synodontis membranaceous. Mud deposit feeders are Labeo coubie and L. parvus.

Worthington, E. G. 1966. Introductory survey. In Man-Made Lakes, ed. R. H. Lowe-McConnell, pp. 3-6. Symposium Inst. Biol., no. 15. London: Academic Press.

[A general survey of man-made lakes (including Lake Volta) in Africa.]

Wuddah, A. A. 1967. A bibliography of Tilapia (1930-1967). Volta Basin Research Project Tech. Rept., X 20. University of Ghana, 9 pp.

[An incomplete but useful bibliography of the genus Tilapia. Thys van den Audenaerde's annotated bibliography (1968) is at present the most complete annotated work on Tilapia.]

INDEX OF AUTHORS

Adiase, M. K., 277
Attionu, R. H., 277

Beauchamp, R., 277
Biswas, E., 278
Biswas, S., 279, 280, 281, 282, 283
Blanc, M., and J. Daget, 284
Brooks, M., 284
Butcher, D.A.P., 284

Czernin-Chudenitz, C., 285

Daget, J., 285, 286
Daget, J., and A. Iltis, 286
Denyoh, F.M.K., 286

Entz, B., 288, 289
Evans, W. A., and J. Vanderpuye, 289, 290
Ewer, D. W., 291

FAO, 291, 292
Freshwater Biology Abstracts, 292

Hall, J. B., E. Laing, M. Hossain and G. W. Lawson, 292
Hall, J., P. Pierce and G. Lawson, 293
Holm, L. G., L. W. Weldon, and R. D. Blackburn, 293

Institute of Aquatic Biology, 293
Irvine, F. R., 293

Lawson, G. W., 293, 294
Lawson, G. W. et al., 295
Lawson, G. W., T. Petr, S. Biswas, E.R.I. Biswas, and J. D. Reynolds, 296
Lelek, A., and A. A. Wuddah, 299

Obeng, L. E., 299, 300

Petr, T., 300, 301, 304, 305, 306, 307, 308, 309
Petr, T., and J. D. Reynolds, 310
Pierce, P. C., 310, 311
Pierce, P. C., and A. Opoku, 313
Proszynska, M., 314

Index of Authors, continued

Rajagopal, P. K., 315
Ram, J., 315
Regier, H. A., 315
Reynolds, J. D., 315, 316, 318, 319, 320
Reynolds, J. D., J. A. Adetunui, and
H. O. Ankrah, 320
Roberts, T., 320
Roman, B., 321

Taylor, B. W., 321
Taylor, G. T., and J. McAlister, 321
Thys van den Audenaerde, D.F.E., 321

Vanderpuye, C. J., 321, 322
Viner, A. B., 322, 323, 324
Volta Basin Research Project, 324

White, E., 325
Whitehead, V., 325
Worthington, E. G., 325
Wuddah, A. A., 326

APPENDIX 4

PARTIAL INVENTORY OF FLORA AND FAUNA

Phanerogamic Vegetation of Lake Volta

1. Free-floating on the surface.

ARACEAE
Pistia stratiotes Linne

SALVINIACEAE
Azolla africana
Salvinia nymphellula

LEMNACEAE
Lemna paucicostata
Wolffia arrhiza
Spirodela polyrrhiza
Wolffiella welwitschii

2. Free-floating below surface.

CERATOPHYLLACEAE
Ceratophyllum demersum
Ceratophyllum submersum

LENTIBULARIACEAE
Utricularia inflexa
Utricularia reflexa
Utricularia gibba

3. Free-floating on surface and rooted.

NYMPHAEACEAE
Nymphaea lotus
Nymphaea maculata
Nymphaea rafescens

PONTEDERIACEAE
Eichhornia natans
Heteranthera callifolia

MENYANTHACEAE
Nymphoides indica

ALISMACEAE
Sagittaria guyanensis

Phanerogamic Vegetation (Continued)

4. Free-floating below surface and rooted.

VALLISNERIACEAE
Vallisneria spiralis

NAIADACEAE
Naias pectinata
Naias meiklei

CHAROPHYCEAE
Nitella mucronata
Nitella microcarpa

5. "Sudd" formers.

CYPERACEAE
Cyprus nudicaulis
Pycreus mundti
Scirpus cubensis

GRAMINEAE
Vossia cuspidata
Oryza barthii
Leersia hexandra
Torulinium confertum
Cyclosorus striatus
Echincloa stagnina

AMARANTHACEAE
Ludwigia leptocarpa

6. Rooted and emergent.

CYPERACEAE
Cyperus articulatus
Cyperus digitatus
Eleocharis fistulosa

GRAMINEAE
Echinocloa pyramidalis

TYPHACEAE
Typha australis

POLYGONACEAE
Polygonum senegalens
Polygonum tomentosum

MORACEAE
Ficus congensis

Phanerogamic Vegetation (Continued)

7. Weeds of the wet margins.

CYPERACEAE
Pycreus albo-marginatus

MIMOSACEAE
Mimosa pigra

PAPILIONACEAE
Aeschynomena indica

ORGRACEAE
Ludwigia stolonifera

AMARANTHACEAE
Alternanthera sessilis

COMPOSITAE
Eclipta alba
Endyra fluctuans

List of Phytoplankton and Algae

CHLOROPHYCEAE
Ankistrodesmus falcatus (Corda) Ralfs.
Closterium acutum (Lyng.) Breb.
C. parvulum Naeg.
C. subulatum (Ktz.) Breb.
Cosmarium moniliforme (Turp.) Ralfs.
C. botrytis [(Bory) Menegh.] Ralfs.
Pediastrum simplex (Meyen) Lemm.
Scenedesmus acutus (Meyen) Chod.
S. bijugus (Turp.) Ktz.
S. quadricaudus (Turp.) Breb.
Staurastrum paradoxum Meyen f. *parvum* W. West

BACILLIARIOPHYCEAE
Cocconeis placentula Ehr.
Fragilaria capucina (Bory) Desmaz.
Melosira granulata (Ehr.) Ralfs.
M. granulata, v. angustissima O. Muell.
Navicula radiosa Ktz.
Nitzschia acicularis (Ktz.) W. Sm.
N. sigmoidea (Nitzsch.) W. Sm.
Pinnularia stauroptera (Grun.) Rabh.
Stephanodiscus astraea (Ehr.) Grun.
Synedra acus Ktz.
S. ulna (Nitzch.) Ehr.

Phytoplankton and Algae (Continued)

CRYPTOPHYCEAE
Cryptomonas erosa Ehr.
C. erosa, v. reflexa Marsson

DINOPHYCEAE
Peridinium africanum Lemm.
P. cinctum (O.F.M.) Ehr.

EUGLENINEAE
Trachelomonas ovalis von Daday

CYANOPHYCEAE
Anabaena aphanizomenoides Forti
A. flos-aquae (Lyng.) Breb. B. & Fl.
A va· ' bilis (Ktz.) B. & Fl.
Arthrospira tenuis Bruehl & Biswas
Chroococcus dispersus (Keissl.) Lemm.
Microcystis flos-aquae (Wittr.) Kirchn.
Phormidium tenue (Menegh.) Gom.

Zooplankton of Lake Volta

PROTOZOA
Ciliata

ROTIFERA
Anuraeopsis
Polyartha
Trichocera
Keratella
Filina

ARTHROPODA
Crustacea
Copepoda: Cyclops, Diaptomus
Cladocera: Diaphanomosa
Ceriodaphina
Bosmina
Moina
Bosminopsis

Some Invertebrates of Lake Volta

PHYLLUM ANNELIDA

Oligochaeta
Naididae
Allonais paraguayensis ghanensis Hrabe
Dero digitata (Michaelson)
Nais variabilis (Piguet)
Aulophorus ghanensis Hrabe
Branchiodrillus cleistochaeta Dahl
Enchytreidae
Species not known

Hirudinea
Batracobdella nilotica Joh.
Batracobdella tricarinata Bl.
Helobdella conifera Moore

PHYLLUM MOLLUSCA

Gastropoda
Bulinus forskali Ehr.
Bulinus truncatus Aud.
Anisus coretus Blain.
Ferrissia sp.

PHYLUM ARTHROPODA

Crustacea
Cladocera
Ilyocruplus sordidus Lievon
Copepoda
unidentified

Ostracoda
Cypricercus sp.
Chrissia spp.
Acocypris sp.
Strandesia spp.
Stenocypris sp.
Cyprettinid sp.

Conchostraca
Cyclestheria hislopi Baird

Some Invertebrates of Lake Volta (Continued)

PHYLLUM ARTHROPODA (cont'd)

Arachnida
- Hydracarina
  - unidentified

Insecta
- Ephemeroptera
  - *Caenis sp.*
  - *Cloeon smaeleni* Gillies
  - *Povilla adusta*
- Odonata
  - Anisoptera
    - *Orthetrum sp.*
    - *Acisoma sp.*
    - *Trithemis tillarga* Fab.
    - *Brachythemis tencosticta*
  - Zygoptera
    - *Ecnomus sp.*
    - *Pseudagrion*
    - *Enollagma*
    - *Ischnura senegalensis* Ramb.
- Hemiptera
  - Corixidae
    - *Micronecta christiniana* Lausb.
    - *Micronecta scutellaris*
  - Belostomatidae
    - *Diplonychus grassei*
    - *Diplonychus gr. nepoides*
  - Pleidae
    - *Plea pullula* Stal
  - Nepidae
    - *Ranartra parvipes* Sign.
- Coleoptera
  - *Loccophilus sp.*
  - *Synchortus sp.*
  - *Hydrovatus sp.*
  - *Hydrocanthus sp.*
  - *Canthydrus sp.*
  - *Hydrobiinae sp.*
- Diptera
  - Nematocera - Culicinae
    - *Aedomyia africana* N-L
    - *Ficalbia splendens* Th.
    - *Ficalbia pallida* Ed.
    - *Mansonia africana* Th.
    - *Mansonia uniformis* Th.
    - *Culex poicilipes* Th.
    - *Anopheles squamosus* Th.
    - *Anopheles constani* Lar.
    - *Anopheles gambiae*

Some Invertebrates of Lake Volta (Continued)

PHYLLUM ARTHROPODA (cont'd)

Chironomidae
- *Chironomus scotti* Kieffer
- *Ch. transvallensis* Kieffer
- *Ch. allaudi?* Kieffer
- *Ch. cadipterus* Kieffer
- *Ch. formosipennis* Kieffer
- *Ch. imicola* Kieffer
- *Ch. c.f. imicola* Kieffer
- *Ch. sp. not identified*
- *Dicrotendipes sudanicus* Freeman
- *D. cordatus* Kieffer
- *D. kribiicola* Kieffer
- *D. chloronotus* Kieffer
- *D. multispinosus* Freeman
- *Nilodorum brevibucca* Kieffer
- *N. brevipalpis* Kieffer
- *N. fractilobus* Kieffer
- *N. rugosum* Kieffer
- *Xenochironomus trisetosus* Kieffer
- *Cryptochironomus lindneri* Freeman
- *C. diceras* Kieffer
- *C. forcipatus* Freeman
- *C. acutus* Goetghebuer
- *C. nudiforceps* Kieffer
- *C. sp. not identified*
- *Stenochironomus sp. not identified*
- *Polypedilum deletum* Goetghebuer
- *P. longicrus* Kieffer
- *P. griseoguttatum* Kieffer
- *P. fuscippene* Kieffer
- *P. annulatum* Freeman
- *P. brunneicornis* Kieffer
- *P. dewulfi* Goetghebuer
- *Pentapedilum wittei* Freeman
- *Stictochironomus caffrarius* Kieffer
- *Lauterborniella fuscoguttata* Kieffer

Certaopogonidae
- *Bezzia pistiae*
- *Palpomyia(?)*

Lepidoptera
- *Nymphula sp.*

The Fishes of Lake Volta, Ghana

ORDER CLUPEIFORMES

Notopteroidei
- Notopteridae
  - *Papyrocranus* After Gunther 1868

Osteoglossoidei
- Osteoglossidae
  - *Heterotis niloticus* Ehrenberg 1829

Mormyroidei
- Mormyridae
  - *Hyperopisus occidentalis* Gunther 1866
  - *Mormyrus rume* Valenciennes 1846
  - *M. hasselquistii* Guenther Boulenger 1898
  - *M. macrophthalmus* Gunther 1866
  - *Mormyrops deliciosus* Leach 1818
  - *Petrocephalus bane* Lacepede 1803
  - *P. bovei* Valenciennes 1846
  - *Marcusenius isidori* Valenciennes 1846
  - *M. lhuysii* Steindachner 1870
  - *Gnathonemus senegalensis* Steindachner 1870
  - *G. pictus* Marcusen 1864
  - *G. niger* Gunther 1866
- Gymnarchidae
  - *Gymnarchus niloticus* Cuvier 1829

Clupeoidei
- Clupeidae
  - *Cynothrissa mento* Regan 1917
  - *Pellonula afzeliusi* Johnels
  - *Sierranthrissa sp.*

Cromeriodei
- Cromeriidae
  - *Cromeria nilotica occidentalis* Daget 1954

ORDER TETRAODONTIFORMES

Tetraodontoidei
- Tetraodontidae
  - *Tetraodon fahaka strigosus* Bennett 1834

The Fishes of Lake Volta (Continued)

ORDER CYPRINIFORMES

Characoidei
Characidae
Hepsetus odoe Bloch 1794
Hydrocyon brevis Gunther 1864
H. forskahlii Cuvier 1819
Alestes baremose Joannis 1835
A. nurse Ruppell 1832
A. leuciscus Gunther 1867
A. macrolepidotus Valenciennes 1869
Micralestes acutidens elongatus Dager 1957
M. occidentalis Gunther 1899
Citharinus citharus Geoffroy St. Hilaire 1809
C. latus Muller & Troschell 1845
C. distichoides Pellegrin 1919
Neolebias unifasciatus Steindachner 1894
Nannocharax ansorgii Boulenger 1911
N. fasciatus Gunther 1867
Distichodus brevipinnis Gunther 1864
D. rostratus Gunther 1864
D. engycephalus Gunther 1864

Cyprinoidei
Cyprinidae
Barilius niloticus occidentalis Blache & Miton 1960
Chaelaethiops brevianalis Daget 1954
Barbus ablabes Bleeker 1863
B. nigriensis Boulenger 1902
B. macinensis Daget 1954
B. punctitaeniatus Daget 1954
B. sublineatus Daget 1954
B. pobeguini Pellegrin 1911
B. leonensis Boulenger 1915
B. stigmatopygus Boulenger 1903
Labeo senegalensis Valenciennes 1842
L. coubie Ruppell 1832
L. parvus Boulenger 1902
Varicorhinus wurtzi Pellegrin 1908

Siluroidei
Bagridae
Bagrus spp.
Chrysichthys nigrodigitatus Lacepede 1803
C. walkeri Gunther 1899
Auchinoglanis occidentalis Valenciennes 1840
Porcus bayad Forskal 1775
P. docmac Forskal 1775
Clarotes laticeps Ruppell 1829
C. macrocephalus Daget 1954

The Fishes of Lake Volta (Continued)

ORDER CYRPINIFORMES (cont'd)

Siluroidei
Schilbeidae
Physailia pellucida Boulenger 1901
Schilbe mystus Linne 1762
Siluranodon auritus Geoffroy St. Hilaire 1827
Irvineia voltae Trewaves 1943
Mochocidae
Chiloglanis voltae Daget & Stauch 1963
Synodontis membranaceous Geoffroy St. Hilaire 1809
S. clarias Linne 1762
S. sorex Gunther 1864
S. velifer Norman 1935
S. filamentosus Boulenger 1901
S. violaceous Pellegrin 1919
S. nigrita Valenciennes 1840
S. ocellifer Boulenger 1901
S. gambiensis Gunther 1864
S. schall Bloch Schneider 1801
Amphiliidae
Phraetura clauseni
Malapteruridae
Malapterus electricus Gmelin 1789
Clariidae
Heterobranchus bidorsalis Geoffroy St. Hilaire 1809
H. longifilis Valenciennes 1840
H. isopterus Bleeker 1863
Clarias angullaris Linne 1762
C. walkeri Gunther 1896
C. liberiensis Steindachner 1894
C. ebriensis Pellegrin 1920

ORDER CYPRINODONTIFORMES

Cyprinodontidae
Epiplatys chaperi Sauvage 1882
E. senegalensis Steindachner 1870
E. bifasciatus Steindachner 1881
E. dageti Poll 1953
Aplocheilichthyes normani Dahl 1928
A. pfaffi Daget 1954
Panchas grahami Pellegrin 1933
Aphyosemion spurelli Boulenger 1913
A. petersii Sauvage 1882

The Fishes of Lake Volta (Continued)

ORDER PERCIFORMES

Percoidei
Cichlidae
Hemichromis fasciatus Peters 1857
H. bimaculatus Gill 1862
Pelmatochromis guentheri Sauvage 1862
Leptotilapia irvinei Trewaves 1943
Tilapia galilaea Artedi 1757
T. nilotica Linne 1757
T. zillii Gervais 1848
T. rendalli Boulenger 1896
Centropomidae
Lates niloticus Linne 1762

Anabantoidei
Anabantidae
Ctenopoma kingsleyae Gunther 1896

Ophicephaloidei
Ophicephalidae
Ophiochephalus (Parchanna) obscurus
Parophiocephalus obscurus Gunther 1861

Gobioidei
Eleotridae
Kribia nana chevalieri Pellegrin 1923

ORDER MASTACEMBELIFORMES

Mastacembeliodei
Mastacembelidae
Mastacembelus nigromarginatus Boulenger 1898

ORDER POLYPTERIFORMES

Polypteriidae
Polypterus senegalus senegalus Cuvier 1829
P. bichir lapradii Steindachner 1869
P. endlicheri endlicheri Heckel 1849

ORDER CERATODIFORMES

Lepidosirenidae
Proptopterus annectens anectens Owen 1839