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9. ABSTRACT

To date, guidelines specific to impact assessment of tropical dams have not been developed, particularly as regards hydrobiological and ecological impacts. The need for such guidelines motivated the Agency for International Development to commission the Smithsonian Institution's Office of International and Environmental Programs to undertake a case study in Ghana of Volta Lake, formed by the Akosombo Dam on the Volta River. The purpose was to develop an empirical base of information from which guidelines could be evolved. This was one of three case studies undertaken. The other two studies addressed the environmental impact of rapid urbanization (Seoul, Korea) and the environmental impact of marine pollution by oil in the tropics (Indonesia).

It is hoped that these guidelines will be useful for planners of future tropical dams, as well as for managers of existing dams, who are concerned with obtaining the best information possible on the potential environmental impacts of these important public investments. It is further hoped that these guidelines will be improved over time as our knowledge of the man-made lake ecosystem in the tropics increases.

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The Environmental Impact of a Large Tropical Reservoir:

Guidelines for IMPACT ASSESSMENT

Based Upon a Case Study of Lake Volta, Ghana, in 1973 and 1974

By Peter H. Freeman

Office of International and Environmental Programs
Smithsonian Institution
Washington, D.C. 1974

PREFACE

A range of costly environmental impacts are known to be generated by impounding tropical river systems. In particular, research and surveys undertaken in connection with large African dams have illuminated the seriousness of biological, hydrological, human health, and other impacts that accompany large tropical impoundments. Knowledge of the magnitude of these impacts has led some to conclude that such projects produce more costs than benefits. But for developing countries poorly endowed with alternative sources of energy, there presently is little choice other than to exploit hydropower potentials. The rising prices of petroleum make hydropower an economic necessity for such countries if a certain degree of autonomy in energy production is to be achieved. Nevertheless, the adverse impacts of large dams should be minimized to the extent feasible and economical, and therefore they must be anticipated. The assessment of potential environmental impacts is the first step towards this end.

To date, guidelines specific to impact assessment of tropical dams have not been developed, particularly as regards hydrobiological and ecological impacts. The need for such guidelines motivated the Agency for International Development to commission the Smithsonian Institution's Office of International and Environmental Programs to undertake a case study in Ghana of Volta Lake, formed by the Akosombo Dam on the Volta River. The purpose was to develop an empiricial base of information from which guidelines could be evolved. This was one of three case studies undertaken. The other two studies addressed the environmental impact of rapid urbanization (Seoul, Korea) and the environmental impact of marine pollution by oil in the tropics (Indonesia).

The study of Volta Lake was done in collaboration with the Volta River Authority in Ghana. In 1973 a review was carried out of a number of environmental aspects associated with the impoundment of the Volta River. The study was undertaken by eight scientists who were selected in consultation with the Volta River Authority and whose names appear in the introduction to Part III.

The guidelines presented here evolved largely from the Volta Lake experience but also took into account published work on other man-made lakes in the tropics. The structuring and content of these guidelines was greatly facilitated by antecedent works, particularly Karl Lagler's excellent volume titled *Man-Made Lakes; Planning and Development* (FAO, 1969) and the treatment of river basin projects in *Ecological Principles for Economic Development* (R. Dassmann, J.P. Milton, and P.H. Freeman, 1973). Another valuable antecedent was the World Bank's checklist of questions that should be answered for the purposes of assessing large water-development projects (World Bank, 1973, *Environmental, Health, and Human Ecologic Considerations in Economic Development Projects*).

It is hoped that these guidelines will be useful for planners of future tropical dams, as well as for managers of existing dams, who are concerned with obtaining the best information possible on the potential environmental impacts of these important public investments. It is further hoped that these guidelines will be improved over time as our knowledge of the man-made lake ecosystem in the tropics increases.

The author acknowledges the helpful critique on early versions of this document by Mr. William L. Eilers, Dr. Robert Higgins, and Dr. Katherine Kerby, Smithsonian Institution; Dr. James Lee, World Bank; Mr. Bill Long, U.S. Agency for International Development (USAID); Dr. Robert Goodland, New Botanical Garden, The Cary Arboretum; Mr. Phillip Pierce, U.S. Army Corps of Engineers; Mr. Christian de Laet, consultant to the United Nations Environment Program; and the consultants who contributed to the Volta Lake case study (see Part III, Introduction). The work of the typists--Mrs. Venka MacIntyre, Pat Carstater, and John Harris--also is acknowledged.

This guidelines booklet is based on a case study titled *Environmental Aspects of a Large Tropical Reservoir: A Case Study of the Volta Lake, Ghana* conducted in cooperation with the Volta Lake Authority, Ghana. The guidelines and case study were prepared by the Smithsonian Institution for the Agency for International Development under A.I.D. contract csd-2608. The Smithsonian Institution is grateful for assistance extended by A.I.D. personnel in Washington and Accra in implementing the study and in formulation of the guidelines.

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I. INTRODUCTION

Dams are being built at an accelerating pace throughout the world to produce energy and to store water for irrigation and other purposes. The value of hydropower potentials has recently been dramatized by the world energy crisis. While only 10 percent of the world's streamflow is now regulated by reservoirs, the proportion is expected to reach two-thirds of the total by the year 2000 (Szesztay, 1973). Many of the world's future reservoirs will be in the tropics, where some of the largest dams in the world have already been built, and especially in Africa (Table 1). More large reservoirs in the tropics are planned. The proposed Pa Mong dam on the Mekong, if constructed, would cost $1.0 billion, store 96 km^3 of water, and control an average annual runoff of 145 km^3. The reservoir surface would cover slightly over 4,000 sq km in Thailand and Laos and have a power capacity of approximately 2,400 megawatts (U.S. Department of Interior, 1970). In Brazil, the Sobradinho dam on the Sao Francisco River will create a shallow, 4,500-sq-km reservoir with a 12-m drawdown. It will dislocate some 70,000 persons.

Large dams have produced great benefits to tropical developing nations. They supply the energy required for heavy industry (e.g., aluminum refining in Ghana), for light industry (e.g., textile mills in the U.A.R.), and for urban and rural electrification. Water stored behind dams also can help realize the promise of high-yielding grains by providing the controlled water supply which is essential for their succesful cultivation. Further, large dams have become a symbol of modernization and a powerful force of political unification.

Against these benefits must be weighed certain ecological and human problems which are unique to tropical man-made lakes. Water weeds have affected tropical man-made lakes in various degrees of severity. They obstruct navigation and fishing, increase water loss through transpiration, clog pen-stock intakes, and provide habitat for a number of vectors of serious diseases, especially malaria and schistosomiasis. The alarming spread of schistosomiasis among populations in the African continent has been a consequence of the spread of the intermediate snail host in man-made lakes and downstream irrigation systems where favorable habitat conditions have been created. Of great consequence is the fact that, as yet, satisfactory solutions have not been found for either of these unique tropical problems of water weeds and schistosomiasis. They frequently, but not always, are ecologically related.

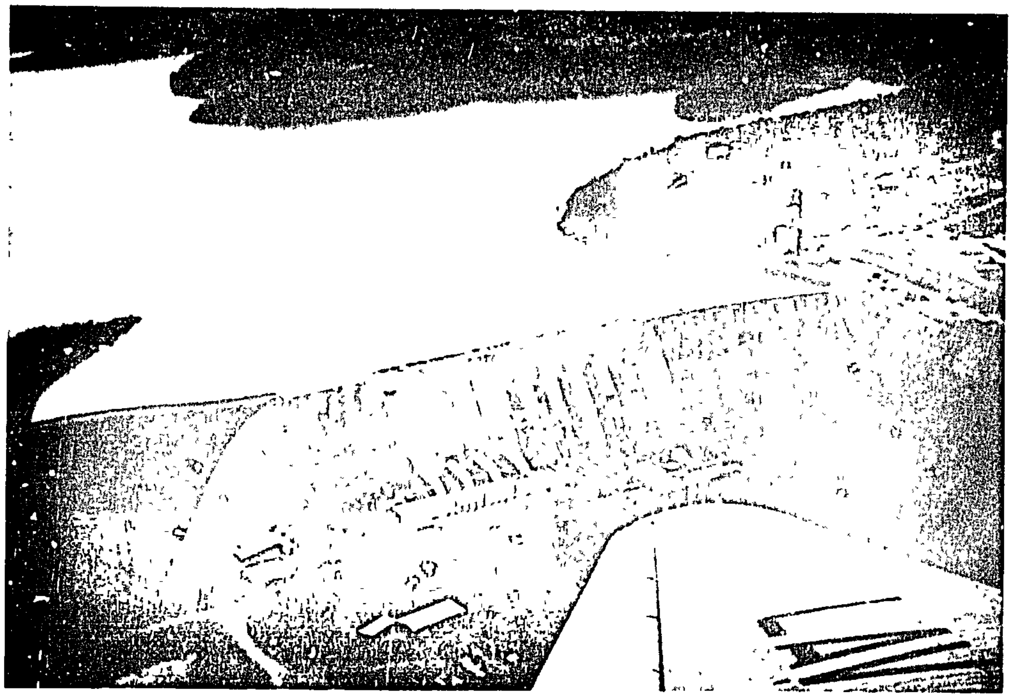


Plate 1. The Guri Dam on the Caroni River, Venezuela.

Table 1 Characteristics of five man-made lakes in Africa

Dam	Date of closure	Hydropower capacity (mw)	Name of lake	Volume (km^3)	Reservoir surface (km^2)	Depth of drawdown	Number of people resettled	Estimated annual sustainable fish production (metric tons)	Number of fishermen
Akosombo Volta R., Ghana	1964	768	Volta	140-165	8,730	3 meters (ave.)	88,000	40,000	20,000 (1969)
Kariba Zambezi R., Zambia, Rhodesia	1958	800	Kariba	147	5,000	3 meters	57,000	20,000	n.d.
Kainji Niger R., Nigeria	1966	960	Kainji	11.5	1,280	10 meters	50,000	10,000	n.d.
Aswan High Dam, Nile R., UAR	1964	10^7/yr	Nasser	132	5,000	n.d.	120,000	10,000	5,000 (1973)
Kossou Bandama R., Ivory Coast	1971	175	Kossou	20	1,600	n.d.	100,000	16,000	n.d.

Sources: Work by various authors published in Obeng, 1969; Farvar and Milton, 1973; and Ackerman et al., 1974.

Also relatively unique to tropical dam projects are the great numbers of people who have to be resettled from impoundment areas. Resettlement is costly both socially and economically. Only 14,000 families were relocated because of the 20 dams in the Tennessee Valley system (Scudder, 1973), while the Volta dam alone dislocated more than 80,000 people and the Pa Mong would flood out more than 250,000 at the 240-meter level. In temperate zones, the land-use capabilities of reservoir sites do not tend to support dense populations. But in the tropics, where glaciation has not produced vast fertile plains as in North America, alluvial and floodplain soils tend to be the richest farmlands and the most densely populated. In the drier tropics, access to water is another important reason for dense populations in river valleys.

Other problems virtually universal to dam projects include loss of reservoir capacity from evaporation and/or sedimentation, obstruction of fish migrations, and perturbation of downstream hydrology and aquatic systems, including estuaries. The impacts of altered freshwater-flows to estuaries are the least understood of the downstream impacts but potentially are the most important. Many marine as well as coastal fish are biologically adapted to the seasonal flux of terrestrial runoff. The expected regulation of two-thirds of the world's running waters by the year 2000 is likely to have a great effect on world fisheries production. Impacts of the Aswan High Dam on Mediterranean fish production exemplify the seriousness of this problem.

Many of the problems associated with tropical reservoirs have been the object of postconstruction technical and financial assistance provided by the United Nations specialized agencies (FAO, WHO, UNESCO, etc.) through the United Nations Development Program (UNDP) or bilaterally by aid-giving nations such as the U.S.A. and Canada. The costs of UNDP programs carried out by the Food and Agriculture Organization (FAO) and designed to solve "secondary" problems in four major African dam projects have totaled slightly more than $8.8 million (Table 2). These programs have focused on research and training in fisheries, limnology, hydrology, epidemiology, and agricultural systems. Other agencies such as the World Health Organization (WHO) and UNESCO have focused on other management problems. In connection with Lake Nasser, UNESCO is spending $992,600 to study coastal erosion resulting from the diminished flow at the Nile delta. Participation by the U.A.R. amounts to $1.1 million. Another $974,000 is being used to fund the integrated development and settlement of new lands irrigated by the Aswan High Dam waters where special drainage measures are needed in this dry climate to prevent salinization now that annual flushing of salts by floodwaters has ceased. The needed remedy, determined by an earlier FAO pilot project, is tile drainage, which would cost an estimated $147 million. More recently, a five-year study of water quality in the lake and the river was begun by the U.A.R., and this study will cost the equivalent of $1.0 million.

Plate 2. Aquatic weeds on Volta Lake, Ghana. The *Ceratophyllum* weed held in this researcher's hand is a dominant submerged weed of Volta Lake. The *Bulinus* snail, intermediate host of urinary schistosomiasis, is especially numerous in this weed, which has proven difficult to control.

Table 2 Costs of UNDP programs for four African man-made lakes

Lake	UN Special Fund allocation*	Government counterpart contribution in kind
Kainji	$ 1,259,100	$ 789,527
Kariba	612,100	552,000
Nasser	1,722,700	961,320
Volta	1,336,000	1,618,000
	$ 4,929,900	$ 3,920,847

*Approximately 10 percent of the total is contributed by recipient governments toward local operating costs.

Source: Lagler, 1969, pp. 65-70.

The costs of these programs have not tended to be included in the initial financing of hydropower projects construction and operation, with the result that the cost/benefit analyses are not accurate from a macroeconomic and social accounts standpoint. Because international or bilateral aid usually entails expenditures on the part of recipient governments as well as the international community, the costs of the solution of various unwanted impacts have tended to be diffused. Nevertheless, they are real costs which must be aggregated with design, construction, and operation costs. The recent and persistent gap between the demand and supply of development financing argues strongly that all costs be accurately assessed in order to obtain efficiency in the short- and long-term use of available funds, both in recipient countries and from international sources. To do so, all possible impacts of dams must be identified, and the costs of the avoidance and management of unwanted impacts must be estimated to the extent possible. The guidelines formulated in this document reflect such consideration.

A. ANTECEDENT STUDIES OF TROPICAL RESERVOIRS

Most published research on tropical man-made lakes centers on African reservoirs. Volta Lake has been particularly well studied, although major informational gaps concerning its mineral cycle, sedimentation, and groundwater regime still exist. Aziz (1973) reviewed much of the hydrobiological literature on Volta Lake that resulted from research undertaken in conjunction with the University of Ghana's Volta Basin Research Project and later with the UNDP-sponsored Volta Lake Research Project. Currently, a systematic and comprehensive review of all work and data existing for the lake is being carried out by Dr. Gernot Bretschko under the auspices of UNESCO. Much of the Volta Lake research is collected in *Man-Made Lakes, The Accra Symposium* (Obeng, 1969).

Research on other African man-made lakes is collected in volumes edited by Lowe-McConnell (1966) and Visser (1970). For Lake Kariba, Coche (1971) has prepared an annotated bibliography of 155 references published before 1969, plus 45 references in press or under preparation. Recent research on man-made lakes around the world is collected in the proceedings of the 1971 Knoxville Symposium on Man-Made Lakes (Ackermann et al., 1973). Studies on various adverse impacts of tropical dams have also focused on African projects. Much of this work is collected in Farvar and Milton (1972) and Ackermann et al. (1973). Resettlement problems have received considerable attention from social scientists; and, again, the Volta Lake resettlement is one of the better documented experiences (Chambers, 1970). In Southeast Asia a general appreciation of the possible impacts of the Mekong River dam system has been undertaken (Challinor, 1973), and the Smithsonian Institution's Office of International and Environmental Programs currently is studying the probable ecological effects of raising the water level of the Nam Ngum Dam. The office is also studying the biology and ecology of intermediate host snails of schistosomiasis in the Lower Mekong River (Schneider, 1974).

In nations situated at higher latitudes, the concern for adverse impacts also has motivated reviews, such as that of Hagan and Roberts (1972) on ecological impacts of dams in California. The U.S. Water Resources Council took into account ecological impacts of dams in defining principles and standards proposed for planning water and related land resources (Water Resources Council, 1971). U.S. water development experiences are mentioned for their analytical focus rather than the substance of the problems, which in higher latitudes are different from those of the tropics. Some of the above-mentioned works contain guidelines for planning assessment and management, and these are reviewed later.

The considerable gaps in our understanding of tropical man-made lakes have been underscored by several authorities. The Scientific Committee on Problems of the Environment (SCOPE) of the International Council of Scientific Unions (ICSU) recently reviewed dams and man-made lakes from the ecosystem points of view (SCOPE, 1972). This document, which synthesized the state of knowledge as of 1971, was drafted after the 1971 International Symposium on Man-Made Lakes (Ackermann et al., 1973) by a special working group organized under SCOPE. Providing an excellent summation of knowledge on these ecosystems, it presents for the first time a framework for understanding the various stages of evolution of a man-made lake. Our limited understanding of biological production in tropical reservoirs was cited as a constraint on predicting fisheries potentials in preimpoundment studies.

Research needs in the context of tropical reservoirs and other major ecosystem modifications have been reviewed by a group of international scholars convened by the Institute of Ecology (Farnworth and Golley, 1974). Expanded studies of the biogeochemistry of major tropical drainage basins were recommended; the nature of eutrophication in tropical water bodies was said to need more research; and surveys were recommended of the physicochemical characteristics of water in drainage basins now or soon to be subject to significant alteration.

Other researchers (Lewis et al., 1973) have pointed out the paucity of information on the nitrogen and phosphorus cycle in tropical reservoirs and on the corresponding influence on primary production. Also needing better study is the contribution by flooded terrestrial vegetation to tropical reservoirs. Vegetation in tropical ecosystems has a greater nutrient store, relative to nutrients available in the soil, than is the case in ecosystems of higher latitudes. However, apart from a few pioneering studies, Odum, 1970, and Fittkau and Klinge, 1973; see also Farnworth and Golley, 1974), quantification of nutrients stored in the biomass of different classes of tropical plant communities remains to be done. Finally, still to be clarified are the reasons for the apparent high productivity of tropical lakes relative to temperate zone lakes.

B. ANTECEDENT GUIDELINES

As the ecological problems of tropical reservoirs--particularly those in Africa--became manifest and better understood during the 1960's, biologists and other life scientists quickly perceived the need to orient such investments better. Although recommendations for research of various problems had been formulated in at least one major symposium on man-made lakes (Lowe-McConnell, 1966), the full range of relationships of the various ecological problems and the economic and social aspects of dam projects were not adequately developed until 1969 when FAO published *Man-Made Lakes: Planning and Development* under Karl Lagler's editorship. The significance to development of the ecological problems of man-made lakes was clearly focused in several contributions to a conference on the Ecological Aspects of International Development held in 1968 (Warrenton, Virginia), the proceedings of which were later published in *The Careless Technology, Ecology and International Development* (Farvar and Milton, 1972). That conference helped to stimulate international development agencies to review explicitly the environmental impacts of dams and other development projects (World Bank, 1973). Further, it gave impetus to the preparation of *Ecological Principles for Economic Development* (Dassmann et al., 1973) under the cosponsorship of the International Union for the Conservation of Nature and Natural Resources and the Conservation Foundation. A major chapter in that book deals with river basin development.

Each of these antecedent works has a slightly different focus and a brief description is merited.

Man-Made Lakes; Planning and Development is intended as a guide "for use in the earliest stages of planning a man-made lake to minimize human stress and maximize the overall social and economic achievement through timely consideration of secondary impacts" (Lagler, 1969, p. vii). This work draws from a decade of FAO experience in technical assistance programs related to African man-made lakes, and the reference to "secondary" problems reflects an earlier, relatively narrow focus on hydropower projects, at least within the context of economic and financial analysis. This slender publication (71 pages) is succinct yet comprehensive and deals with economic, social, and public health programs; agriculture and livestock production related to drawdown and irrigation land use; forestry and forest produce industries in the catchment and downstream; commercial and subsistence fisheries in reservoirs; wildlife recreation and tourism; navigation and water safety; surface and groundwater; water quality; and aquatic nuisance plants. Recommendations for planning, research, and management of all the major problems and issues in man-made lakes are set forth in this valuable volume.

The increasing recognition of the serious and sometimes intractable problems of tropical reservoirs is reflected in the discussion of river-basin development projects in *Ecological Principles for Economic Development,* whose objective is to "provide the planner with a framework for more adequately assessing the total costs and benefits of a project and for better anticipating the types of information and management needed to minimize adverse environmental impacts and their associated socioeconomic costs" (Dassmann et al., 1973, p. 184). This work summarizes knowledge accumulating from the Aswan project, the Mekong project, and other dams in the tropical world which have been under increasing study and assessment; also, it emphasizes some of the more persistent and recurring problem areas: fisheries, diseases associated with aquatic systems and aggravated by reservoirs, aquatic weeds, watershed management, and human problems of resettlement. Research, survey, and management guidelines pertinent to these problems are interspersed throughout the text in the form of recommendations. Questions were not formulated in the context of impact assessment; however, the World Bank and USAID were in the process of developing such questions.

The World Bank's publication *Environment, Health and Human Ecologic Considerations in Economic Development Projects* contains a section on dams that sets forth a series of questions for orienting the Bank's staff in "the detection, identification and measurement of environmental and related human ecologic effects [of dams]" (World Bank, 1973, p. vi). The questions are intended as general points of departure for analyzing various consequences of proposed dams. In this respect they are more closely attuned to the needs of project analysis than are the other two publications; however, summaries of expected problems are not presented. The questions are grouped into six major categories: environmental/resource linkages, operations, project design and construction, sociocultural factors, health impacts, and long-term considerations. The complete list of questions appears in the appendix.

If answered comprehensively, the World Bank's questions in its guidelines for dam projects should result in a rather complete assessment, provided that the full costs of correcting or avoiding impacts are estimated. For instance, if major public health problems can be anticipated, management and research needs must be defined and their costs estimated as accurately as possible in order to develop a comprehensive appraisal of project costs.

Many of the assessment questions formulated by the World Bank can be answered by "yes" or "no." For example, "Will new public health problems arise as a result of the project?" The public health problems associated with tropical impoundments have several dimensions, and the answer to this question, leading to an assessment of this particular impact, must consider not only the influence of the dam and the man-made lake on disease vector occurrence and habitat conditions but also on the human exposure factor as affected by fishing, water for drinking and bathing, contamination with human wastes, movement on the lake, the possibilities of parasite introduction by populations drawn to the construction, and employment or fishing potentials of the new lake.

Organization of an environmental assessment in terms of all possible impacts is clearly a complex exercise. Hagan and Roberts (1972) developed a very useful checklist of impacts with respect to water projects in California. Impacts are subsumed under the following headings: in the impoundment area; downstream from the impoundment in (a) the river channel and floodplain and (b) the delta, bay, or ocean; and in the areas of projected water use, including rural and urban areas. Although the physiographic context is California, the organization of the impacts is done within a framework that could be adapted to other environments.

C. Objectives and Presentation of the Guidelines

The guidelines for the assessment of tropical dam impacts presented here draw from the aforementioned antecedents and attempt to improve upon them by developing the context for the various questions that should be asked. The objective is to summarize all possible ecological and related physical environmental impacts of tropical dams and man-made lakes within a framework suited to the needs of the impact-assessment procedure.

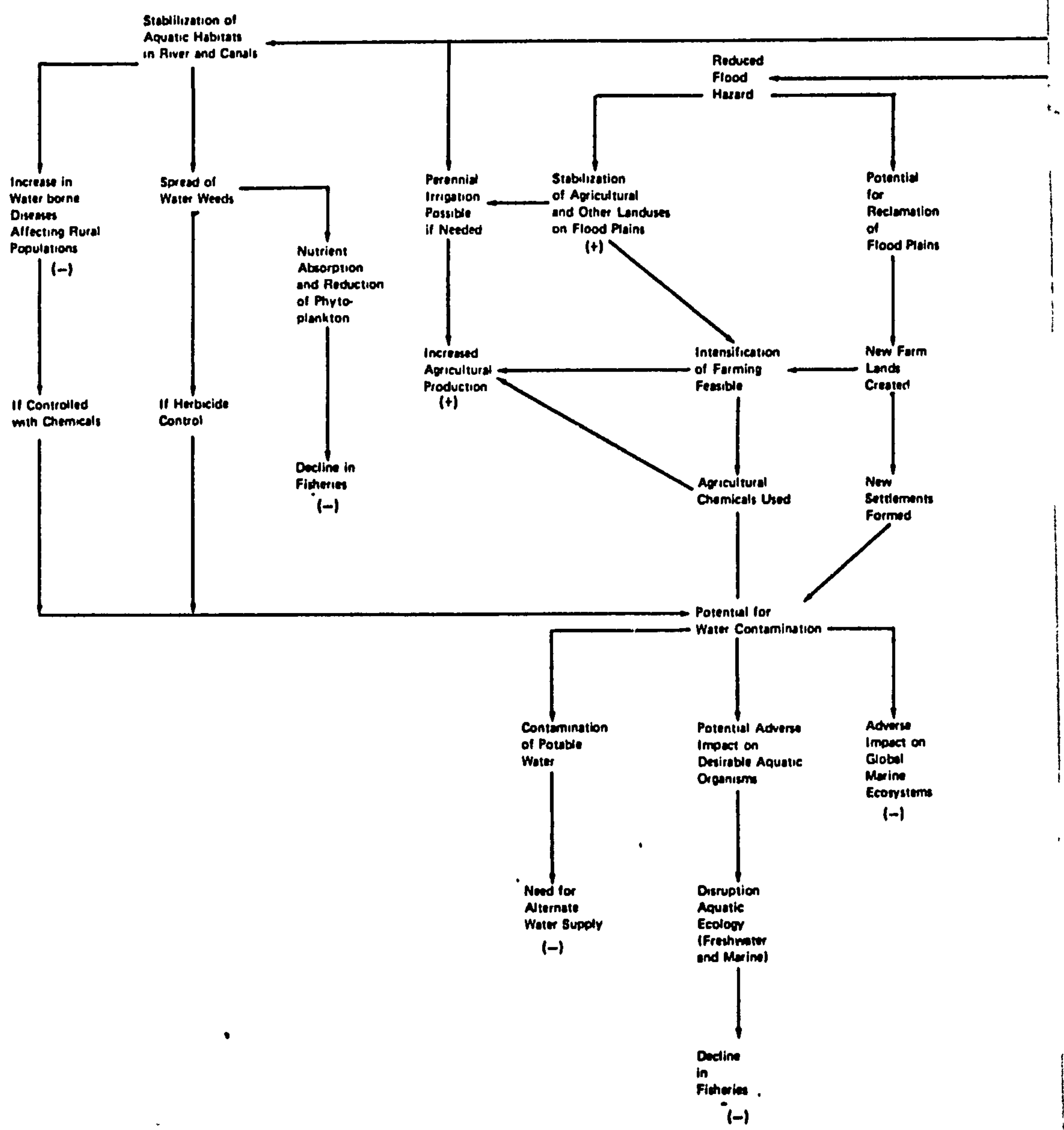
On the basis of the Volta Lake case study and other published experience, a brief narrative of likely impacts is presented. This is followed by key questions that should be asked to determine impacts. Data requirements and alternative methodologies (e.g., research, survey, inventory, evaluation, monitoring) are given to assist in the design of the assessment study. It is hoped that in this way the considerable amount of literature and experience on various ecological problems is presented in a fashion directly useful to planners, whether in international or national development agencies.

In the first section, guidelines are presented for the environmental assessment of alternative impoundment sites. The second section presents guidelines for assessing in further detail the hydrobiological impacts of sites once they are selected.

A simplified graphic treatment of the various consequences of impoundment of a tropical river is presented in Figure 1. The nature, importance, and magnitude of impacts will vary considerably from one reservoir to another due to the influence of a number of variables: size, shape, and depth of reservoir; inflow and outflow rates; range of fluctuations in water level; climate and weather; geology, geomorphology, and soils in the watershed, along the reservoir shores, and in affected downstream areas; tectonic characteristics of the reservoir site; vegetative cover in the reservoir site; distance of the reservoir from the sea; riverine flora and fauna which may be affected by the impoundment; importance and value of resources and features to be flooded; and types and extent of human and animal diseases associated with the aquatic system. The summary of impacts attempts to accommodate these variables.

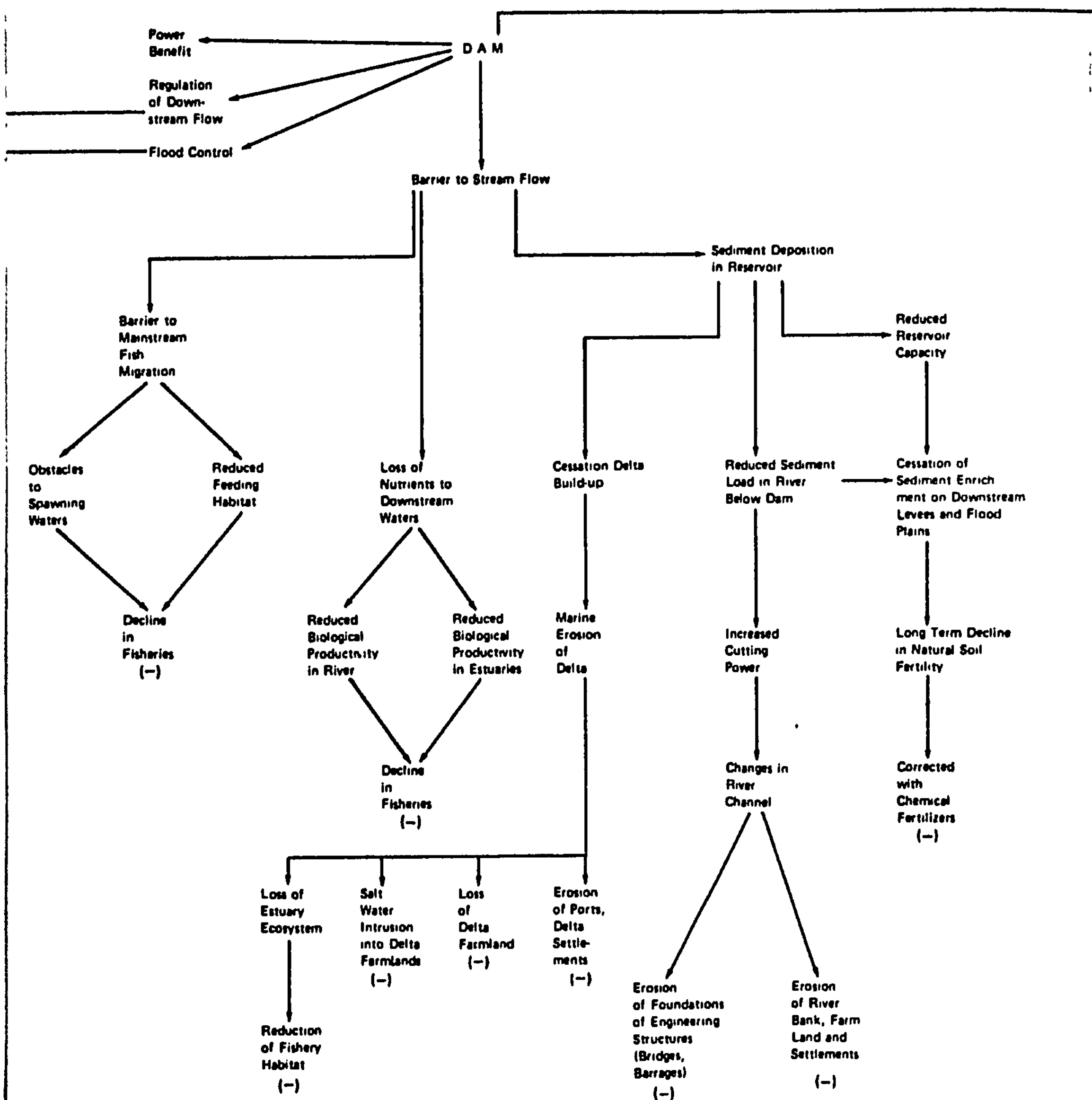
Immediate as well as long-term impacts are generated by dams. The initial impacts of dam closure create profound perturbations in the natural environment and traumatic changes for people whose settlements are inundated. Like the outward-moving ripples of a pebble dropped into a quiet pool, these impacts can be traced through the ecosystems and social systems. Unlike the pool, however, the initial serene stability is not regained. Adjustments in nature and society to the initial impacts may produce additional environmental and human impacts. A different level of stability and ecosystem functioning evolves, and the principal determinants of this level are the dam itself and the uses made of its water.

DOWNSTREAM HYDROLOGY AND LAND USE



POTENTIAL ENVIRONMENTAL CONSEQUENCES OF A TROPICAL DAM

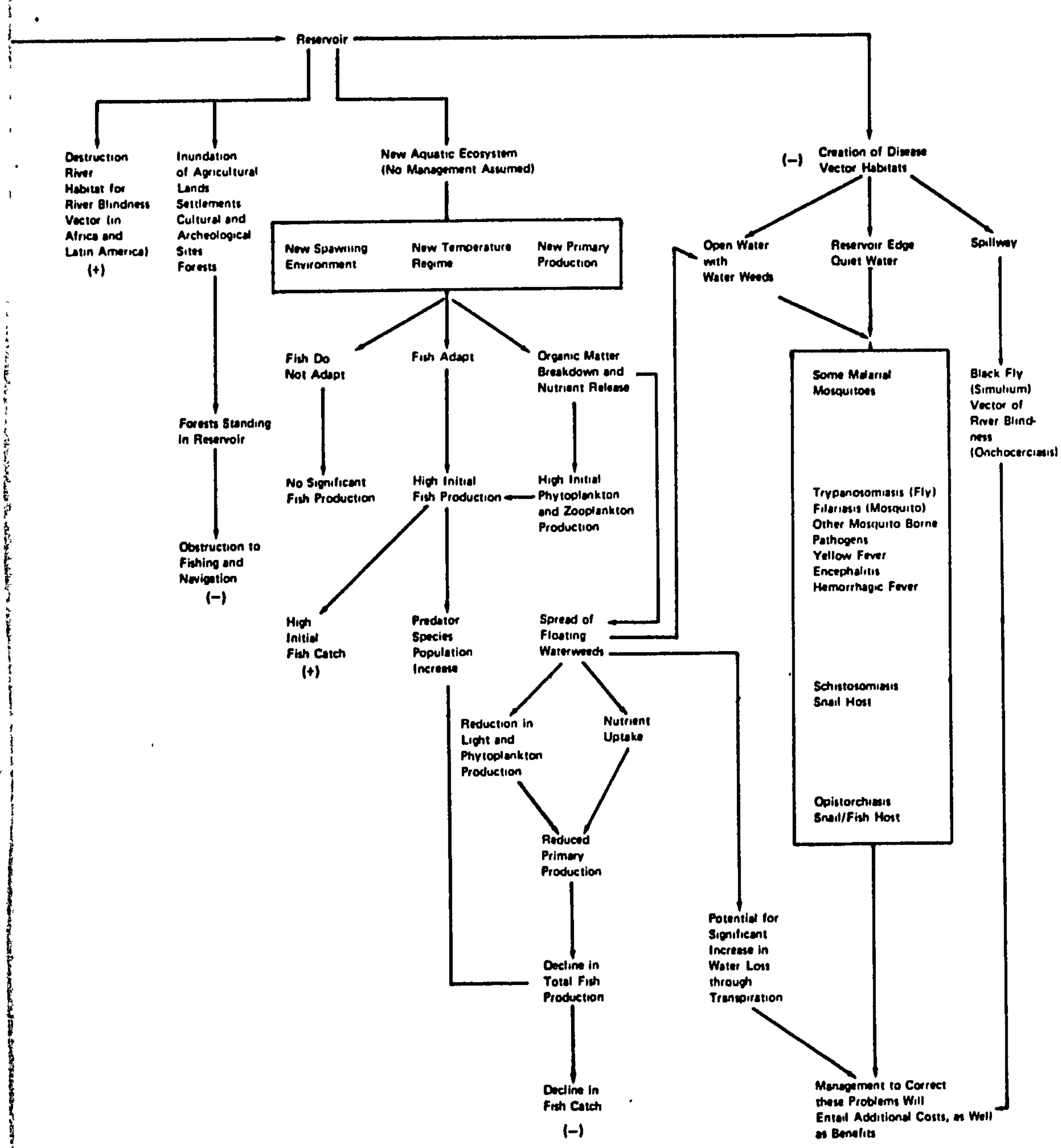
Benefits (+) Costs (−)



EROSIONAL PROCESSES

Prepared by Peter H. Freeman and John P. Milton.c Threshold, Inc.

MAN MADE LAKE



PART II: ASSESSMENT GUIDELINES

The environmental assessment of large dams, whether in the tropics or higher latitudes, must take into account the size and complexity of these projects and the complexity of running-water systems. Great amounts of time, money, and organizational effort precede the construction of a dam and hydropower project. During the preinvestment stage a large-scale project gathers its own political and institutional momentum and becomes an increasingly more substantial commitment by governments. To the extent that these conditions create inflexibility in design, environmental impact studies should be initiated as early as possible, in conjunction with studies for site selection. Moreover, the ecology of running-water systems requires at least a full year of observations if adequate assessments are to be made of impoundment impacts on a river for site-selection purposes. Meteorological and hydrological factors should be studied for as many years as possible. More detailed studies and observations are needed to predict impacts and guide the management of an impoundment once a site has been selected.

The environmental assessment of tropical reservoirs should begin with an assessment of various potential reservoir sites in the context of general studies aimed at developing information on the hydropower potentials of a nation. Most nations have already identified potential sites on the basis of river volume and topographic characteristics related to impoundment. These and other potential sites should be assessed in terms of environmental impacts and the results incorporated into the selection of the best sites, for which more detailed preinvestment studies are to be undertaken. Guidelines for assessments at this level are presented in the first section of this document.

The regulation of the flow of major rivers can have important impacts on the productivity and stability of estuaries and coastal waters. *Any nation which embarks upon a long-range program of hydropower development should carry out complementary assessments of those coastal zone resources which would be adversely impacted by stream-flow regulation.* Since coastal waters and estuaries are known to be the most productive ecosystems in the biosphere--on a par with the productivity of the best alluvial soils under intensive management--and since their productivity is linked to the inflow of fresh water, the combined effects of a series of large dams can generate considerable losses. Comprehensive analysis may indicate that the flow of certain rivers should not be regulated in order to conserve the productivity of important estuaries or coastal waters.

At the level of preinvestment studies (prefeasibility and feasibility studies), more refined data will be required concerning environmental impacts in the reservoir area. These will be needed to determine accurately the time, manpower, and management needs during filling and after filling. At this stage the long-term management needs on the reservoir must be anticipated and related to the data collection and survey efforts. Guidelines for this level of environmental assessment are presented in the second part of this document.

With respect to data needs it is emphasized here, and reiterated in later sections, that prior to impoundment long-term (at least one year) observations are needed of many environmental parameters if an adequate impact assessment is to be performed. The work undertaken in conjunction with Volta Lake (Obeng, 1973) and Lake Kainji (Visser, 1970) is indicative of the kinds of research programs designed to obtain data needed for assessment and reservoir management.

A. ENVIRONMENTAL ASSESSMENT OF ALTERNATIVE IMPOUNDMENT SITES

In this section general guidelines for site evaluation are followed by guidelines for assessing inundation impacts and downstream impacts. It is recommended that the assessments set forth here be carried out for all proposed hydropower or other dam projects which would significantly alter the hydrology of major rivers and create large impoundments.

1. *General Considerations for Damsite Identification*

Volume of flow and topographic conditions suitable for impoundment, dam construction, and the efficient harnessing of the kinetic energy of falling water are priority considerations from the standpoint of hydropower projects. These are standard considerations in the selection of damsites, and most nations have already identified potential sites on this basis. In addition, a preliminary assessment of two environmental considerations affecting site identification should be made. These are climatic and geologic factors which affect reservoir productivity and storage capacity.

First, high productivity in man-made lakes in the tropics can present potentially greater problems than benefits. Productivity is largely determined by mineral inputs to the reservoirs, which, in turn, are determined by watershed characteristics over the long term. If the watershed of the impounded river consists of fertile soils, such as those developed over rocks rich in basic minerals (e.g., olivine, plagioclase, orthoclase, etc.) and especially basic volcanic and igneous rocks, high productivity can be expected. Through weathering, these materials will release the major plant nutrients--nitrogen, phosphorus and potassium--which, either in solution or in sediments, will be carried in runoff to the impoundment by tributary streams. Intractable water-weed problems will develop if adapted riverine species are present (which usually has been the case). The weeds may present good habitat for snail and arthopod vectors of human disease.

Rivers flowing out of nutrient-poor hinterlands--such as watersheds with ancient and well-weathered formations--or zones of acidic (rich in quartz) rocks will cause fewer water-weed problems and probably less sedimentation. The latter is partly a function of erosion due to excessively intense cultivation, which is not normally associated with poor soils. The Guri Dam on the Caroni River in Venezuela exemplifies the impoundment of a nutrient-poor river. This "black water" river is also remarkable in not having major water weeds that might have colonized the reservoir to some degree.

Second, loss of storage capacity through evaporation and sedimentation can be expected in regions with distinct dry seasons in which evapotranspiration potential exceeds actual precipitation. This regime would correspond to the drier tropics. Losses by reservoir evaporation can be computed if meteorological data are available--or evaporation has been measured--and if the surface area of the proposed reservoir is known. Transpiration losses from water weeds can exacerbate evaporation losses. In Lake Nasser, yearly evaporation losses are on the order of 10 to 15 x $10^9 m^3$. If 10 percent of the lake's surface were covered with water weeds, an additional 10 x $10^9 m^3$ would be transpired (Farvar and Milton, 1972, p. 246).

Estimates of sedimentation rates are more subject to qualification, particularly in view of the typical paucity of information on suspended sediment loads in tropical rivers. Sedimentation is also a function of vegetation, topography, and land use as well as climate in the watershed.

In the drier tropics, difficult watershed management problems normally can be expected because climatic conditions are more favorable to human habitation and exploitation than those of the wetter tropics (Dassmann et al., 1973, table 4, p. 208). Cultivation of annual crops and grazing may be major land uses that expose soil to erosion. Natural vegetation in the dry tropics is not as dense or vigorous in regeneration as in more humid zones. Rainfall may come as intense downpours which erode cleared areas. This leads to accelerated erosion in the catchment and sedimentation problems in the impoundment. Land use can be managed to achieve run-off and erosion control, but the full cost of adequate management may entail terracing, changes to crops more protective of the soil, technical and financial assistance for these purposes, enforcement of land-use restrictions, and even modification of land-tenure characteristics. Exploitative and uncertain tenure arrangements will not make it worthwhile for a tenant to invest money or labor in terracing, cover crops, and other soil-conservation methods which would be unprofitable from his standpoint. Thus, early attention must be given to watershed management needs in drier tropical regions.

2. *Seismic and Hydrological Impacts*

The impacts summarized below refer to geophysical and physiographic phenomena that may affect technical and engineering feasibility.

a) *Summary of Impacts*

Added weight to the earth's crust. The weight of the impounded water may increase strain on existing fault planes, resulting in seismic movements during filling. Fluctuations in weight of water because of drawdown may exacerbate the influence on seismicity. Depth of water rather than total volume is the major determinant of the seismic potential.

Interruption of streamflow and alteration of sedimentation and erosion. In the impoundment, coarse sediments eventually will form deltas at tributary mouths; finer sediments will be deposited in deeper waters more distant from shores. Sediment-load of the river system becomes drastically altered as large quantities of minerals are captured by the reservoir. Consequences below the dam are listed in downstream impacts.

Alteration of the groundwater regime. Reservoir water may be lost through permeable formations flooded by impoundment--with desirable or undesirable consequences, depending upon whether loss is absolute or whether economically important aquifers are charged thereby. Groundwater may lubricate fault slippage planes and increase likelihood of movement.

Creation of an extensive surface of water. The lake's surface will change local atmospheric energy balance and may increase local evaporation losses and atmospheric humidity. Such changes will be a function of rainfall, evaporation potential, and wind movement.

b) *Key Questions and Data Needs*

1) *What are the tectonic characteristics of the impoundment region and the damsite, and what are the probable seismic effects of impoundment?*

Data should be collected and analyzed on the frequency, magnitude, effects, and epicenter locations of seismic events that have occurred in the general region of proposed reservoir sites. Major active faults should be mapped and correlated to seismicity as well as to regional geology. In order to develop a history of seismicity, a network of portable seismographs should be installed at the earliest possible time in all areas under consideration for large reservoirs. Data developed from these observations should be analyzed in terms of projected reservoir water-mass and its effects on seismicity. Seismograph measurements should continue during and after the filling-in of those sites where construction is undertaken.

(2) *What is the suspended-sediment load of the river to be impounded, and what are the projected sedimentation rates in the impoundment area? Can high sedimentation rates be countered by design to spill sediments from the reservoir?*

The suspended-sediment load of all major tributaries of the proposed impoundment should be measured over a one-year period, at least, and it should be correlated with flow-volume and with streamflow measurements of previous years if such data exist. Special attention should be given to obtaining measurements immediately after intense rainfall. The morphology of the proposed impoundment site should be determined by topographic survey and assessed in terms of likely sedimentation in order to permit estimates of reservoir capacity loss. Topographic maps of 1:50,000 scale and with contour intervals of 50 feet or less are suggested for reservoir-site mapping.

Sedimentation can be measured by depth-integrating samplers, which are especially useful for sampling during floods. These cost $1,500* or more. Continuous sediment samplers, costing $2,500, can be integrated into stream-gauging stations having automatic recorders and whose instrument costs are $1,000. To these costs must be added installation and construction as well as maintenance and personnel expenses.

(3) *Will reservoir water be captured by permeable geologic formations and lost? If so, how much water may be lost relative to total annual inflow, and what will be the fate of the water transmitted to underground aquifers?*

Geologic mapping of proposed reservoir sites should be undertaken with the help of aerial photointerpretation techniques in order to obtain information on aquifers, permeable formations, and groundwater as indicated by surface geology. Existing wells should be monitored for production at monthly intervals for at least one year to determine normal fluctuations in the water table. Test wells may be needed. Production can be cheaply measured by the bailing method. Seepage studies and water-budget analyses may be needed if aquifers are suspected of conveying significant portions of total runoff. Dyes or radioisotopes tracers may be used to determine the rate, movement and fate of groundwater.

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*Costs are approximate. Figures are taken from *Techniques for Assessing Hydrological Potentials in Developing Countries* (Office of Science and Technology, Agency for International Development, Washington, D.C., 1973, 66 pp.).

(4) *What will be the rate of evaporation loss from the surface of the proposed reservoir at various levels, and what percentage of total annual inflow does this represent?*

To assess evaporation loss, the longest-term data possible are needed on rainfall, temperature, wind velocity, and wind direction. These data can be used to estimate potential evaporation from the reservoir surface at various levels. Surface area must be determined on the basis of topographic maps, already recommended for sedimentation assessments.

Lacking meteorological data, evaporation pans or lysimeters can be installed in the proposed reservoir site. These also can be used to complement and validate calculations from climatic data. They are inexpensive and simple, consisting essentially of containers, such as drums, in which a known quantity of water is allowed to evaporate. Evaporation data should be complemented by rainfall and temperature measurements. A comparison of potential evaporation losses with estimated annual inflow from all sources will provide the basis for determining the relative suitability of alternative reservoir sites, particularly in dry regions where little surface relative to volume would be the optimum condition.

3. *Rivers and Natural Forests*

In all proposed reservoir sites, assessments of the losses from the inundation of stretches of natural rivers and of natural forests should be made. The values of these systems pertain to their functions as habitat, their renewable resources, their minerals, and to their potential values as parks.

a) *Summary of Impacts*

Upon flooding, the decline or destruction of riverine life not adapted to lacustrine conditions will result. In the reservoir site, seasonal fish-spawning and fish-breeding habitats in floodplains may be destroyed or greatly diminished. In some cases, however, flooding and subsequent drawdown may enhance the environment for species that normally spawn in floodplains. This impact will depend upon size, shape, fluctuations in water level, rate of flow-through, and management of the reservoir.

Losses in natural areas of terrestrial ecosystems may include wildlife habitat, unique plant and animal communities with tourism potentials or of scientific value, timber, potential farming and grazing lands, and minerals.

Preimpoundment studies of the river and terrestrial environment of the Lake Brokopondo reservoir site resulted in many new botanical and icthyological discoveries. In retrospect, members of the field survey team judged that had they known beforehand of the uniqueness of the flora and fauna to be flooded they would have promoted dam construction in a different site or different river (Leentvaar, 1973, p. 192).

In remote wildlands in the tropics such as those of Surinam, a long period of research into the flora and fauna should be carried out before final decisions are made on damsite locations.

Trees and other woody vegetation drowned by a reservoir will decompose to a degree, but more resistant parts (trunks, branches) will persist indefinitely, and if left standing will create obstacles to navigation and net fishing, especially in the littoral zone and shallow waters. The costs of clearing should be estimated for each alternative site. As has occurred in Lake Volta, above-water branches may serve to anchor drifting water weeds (sudd). If left standing, dense trees may inhibit vertical mixing of the water column, as was the case in Lake Brokopondo, Surinam. Trees will, however, also provide refugia for fish and substrate for periphyton, which can be an important source of food for fish. In Lake Kainji and Lake Kossou (Nigeria or Ivory Coast) preimpoundment clearing was done in certain areas where fishing and navigation activities were anticipated. *Selective clearing appears to be the best solution.*

Some species of riverine aquatic flora and fauna may adapt to lacustrine conditions in the proposed reservoir, with variable consequences. Also, flooding may destroy the breeding areas or the general habitat of disease vectors such as the tsetse fly (*Glossina* spp.), the black fly (*Simulium* spp.), and anopheline mosquitoes adapted to flowing water (e.g., *Anopheles maculatus maculatus, A. minimus minimus*). But this benefit may be nullified by the possible creation of vector habitats in the new lacustrine environment.

Certain species of river fish may adapt to the conditions of a man-made lake and become the basis for commercial or subsistence fishing. Although the composition and yield of fisheries in proposed reservoirs cannot be estimated with precision, riverine species likely to adapt can be identified and then related to probable productivity of a reservoir as indicated by water quality and reservoir morphology. (More is said on this in Section B.) Adaptable species are likely to be those that tolerate lower levels of dissolved oxygen, seek relatively quiet waters--perhaps with heavy weed growth--for breeding, and are able to feed on a range of plants and animals such as phytoplankton, zooplankton, insects, and perhaps larger plants such as water weeds. In Lake Volta, an insectivorous clupeid that was relatively rare in the Volta River (*Pellonula* sp.) now dominates fish biomass, and, although not presently fished, its predator, *Lates* sp. (a perch), is caught. *Tilapia galilea* (bream) has survived in the distinctly lacustrine conditions of the deepest part of the lake and is fished (Evans and Vanderpuye, 1973). Mormyrids declined following impoundment, as has been the case in Lake Kainji (Salah el-Din el-Zarka, 1973). In the Guri Reservoir, Venezuela, lacustrine conditions have proven especially favorable for one species of piranha (*Serrasalmus spilophleura*), primarily as to breeding habitat (R. Elosegui, personal communication). The species is omnivorous, and it eats other fish as well as seeds.

b) ***Key Questions and Data Needs***

1) *What is the extent and value (economic and scientific) of the natural ecosystems to be inundated? What natural resources will be flooded (e.g., timber, minerals) and what are their present and potential values? Will irreplaceable flora and fauna of genetic or other scientific values be flooded? If so, what measures should or will be taken for their salvage?*

Surveys should be undertaken to determine the quantity and value of timber and mineral resources that may be flooded. The productivity of timber resources and potential agricultural lands should be quantified to assess the permanent loss of these renewable resources. Surveys are needed to determine if rare or endangered flora and fauna may be flooded. Lists developed by the International Union for the Conservation of Nature and Natural Resources (IUCN, 1967) should be used, and local lists should be used if any exist. The time, money, and manpower costs of salvaging desirable species should be assessed. Estimates of the scientific or recreational values of plant and animal communities to be flooded should be made. In little-known areas with extensive natural forests, surveys of flora and fauna will be a major undertaking and adequate time should be allowed. New species are likely to be found, and findings may define botanical or other values of natural areas that may be of great scientific importance.

2) *What species of flora and fauna are likely to adapt to the reservoir? Are they likely to constitute problems or benefits?*

Aquatic species likely to adapt to the reservoir--especially weeds and fish--should be determined by surveys of analogous conditions in the river (e.g., seasonally flooded areas or quiet waters such as oxbow lakes). Existing lakes--natural or man-made--may also indicate the likely composition of lacustrine flora and fauna. A survey of aquatic weeds and fish along the entire length of the river above the damsite should be made with emphasis on lagoons, bays, pools, or other quiet-water areas. For adaptable species which may be important, descriptions of their life histories and habitat requirements should be developed through observations or research. Those fish species which are opportunist feeders and breed all year or in the dry season (i.e., are not dependent on floods for breeding stimulus) should be considered as a first possibility for lake colonization, even though they may be relatively rare in the river system.

3) *Will spawning areas for anadromous and/or potamodromous fish be destroyed by flooding? What would be the significance to fisheries production?*

Anadromous fish migrate from the sea to fresh waters to spawn. Potamodromous fish undertake spawning migrations only in fresh water. The location, extent, and significance of spawning areas used by both categories of fish in the proposed site should be determined by appropriately timed surveys. Future reservoir conditions should be related to lateral spawning habitat needs of potamodromous species. For anadromous fish, the needs for fish ladders or other design solutions should be determined and costed. The extent to which these species are fished should be determined.

4) *How will standing vegetation affect the reservoir? What amount of clearing, if any, should be undertaken?*

Forests and other natural vegetation in the impoundment area should be surveyed and evaluated in terms of navigation and fishing activities in the future reservoir. Aerial photointerpretation methods can be used to advantage. Nature and height of natural vegetation in the potential drawdown area should be given particular emphasis. Topographic maps showing contour intervals and approximate shorelines at different storage levels will be needed to evaluate vegetation in areas where clearing would be needed. The desirability of leaving some vegetation standing should be assessed--using as criteria the feeding and refugia requirements for adaptable fish species--as should fishing methods that are likely to be best for the reservoir. (The role of vegetation in reservoir nutrient status and fisheries is discussed in the section on hydrobiological impacts following dam closure.) Costs of preimpoundment clearing should be estimated.

5) *Will habitats of human or animal disease vectors be destroyed? If so, where are the vectors likely to go (e.g., upstream, downstream, in or around the reservoir), and how will this affect their populations and the human exposure factor?*

Important vectors should be identified and their habitat ecology evaluated in terms of future reservoir conditions. If they are likely to persist in the reservoir area, this possibility should be related to the human-exposure factor associated with lakeside settlement, fishing, and movement of people on the lake. Certain vectors such as the black fly vector of river blindness (in Africa) may move to sites below the dam that are created by the regulated flow (see "Impacts below the Damsite"). The significance of vectors must be assessed in terms of the human or animal host and of the role of hosts in perpetuating the life cycle of parasites.

4. *Archeological Remains*

The values of archeological remains that may be inundated may be very great, although difficult to equate to the values of natural resources such as timber or minerals. An assessment of this impact does not easily lend itself to the standard formulation of the cost-benefit analysis. However, cost estimates of survey, salvage, and relocation operations can be developed. Exploratory surveys are likely to be required for this purpose. Information developed during such work may uncover new finds and improve the evaluation, as has been the case at the Pa Mong damsite. The significance of archeological finds may weigh heavily in the selection of a damsite.

a) *Summary of Impacts*

Important archeological monuments and other artifacts were flooded by the Aswan High Dam; however, the major Nubian temples were salvaged and relocated. In more humid tropical climates, remains of ancient civilizations have been subjected to intense biological and chemical decomposition. Also, heavy vegetative growth frequently tends to mask remains and make discovery and study difficult. In such regions little prior knowledge may exist for the purposes of assessment. However, since river valleys have tended to be important centers of ancient civilizations, it should be assumed that important historical and cultural knowledge may be gained from archeological investigations and that material remains which should be conserved are likely to exist.

b) *Key Questions and Data Needs*

1) *Will any archeological artifacts and other remains be flooded? What is their scientific value? How much work is needed and how much time and money are required to realize their value if it has not been determined?*

2) *What salvage measures would be desirable or required? How much would they cost in time and money? What international authorities would be interested in assisting?*

3) *What religious or other cultural values are attached to archeological remains and sites (e.g., temples, sites of historical or religious significance)?*

Aerial photointerpretation techniques can be used to advantage in reconnaissance archeological surveys of little-known sites. Reconnaissance ground surveys may be needed to determine the needs for adequate studies and for salvage operations. Field surveys should be preceded by reviews of literature and of work already accomplished in the general region.

The costs of necessary studies and surveys should be estimated and the scientific and cultural values of known monuments or sites should be assessed. Salvage and/or relocation costs of important artifacts should be estimated. The possible purposes of salvage, the resources that are available, and the way resources should be allocated should be anticipated. Adams (1973) addresses the question of preimpoundment salvage in detail.

At the national level, the values to society of affected archaeological remains should be determined in consultation with scholars, educators, and religious leaders as well as government officials. These values should be explicitly incorporated into the process leading to site selection for large reservoirs.

5. *Human Settlements and Farmlands*

The flooding of human communities and farmlands has had an important impact in large dam projects in the tropics. An assessment of the resources lost (e.g., farmlands, irrigation systems, houses) and the costs of resettlement should be undertaken for all alternative reservoir sites. These costs should be weighed into preliminary economic analyses of the sites.

a) *Summary of Impacts*

Resettlement of people from reservoir areas has tended to be a complex and costly procedure. In the Volta project, an estimated $34 million was projected to have been spent by 1971 on resettlement of 80,000 people, while the construction cost of the dam and initial hydropower capacity installation was $196 million.

It is axiomatic that if large numbers of people occupy a reservoir site they are sustained by a valuable resource base which would be lost by flooding. Villages frequently are situated on the richer alluvial and levee soils. Increases in existing levels of production may be possible, given technical and financial assistance, and this potentiality should be considered as a long-term opportunity cost.

Fertile areas with a long history of occupation likely will be densely populated and exhibit highly evolved societies and cultures whose adjustment following resettlement will be very problematical. Community farming or grazing lands may include upland soils which would not be flooded, but these will not sustain population densities and production levels possible in more fertile, floodplain areas to be inundated. Villages to be flooded may be contributing little to the modern cash economy and, therefore, may be perceived as a "zero benefit" to the national economy. However, their relocation is likely to generate substantial social and financial costs until human and economic productivity of relocated communities is regained, at least to a subsistence level. This process may be delayed by the trauma of relocation (Scudder, 1973), which is likely to slow adjustment and innovation potentials, and by the need to adopt new methods of farming due to environmental differences. Adequate manpower and institutional capabilities may be lacking for guiding resettlement.

All of these problems affected in some degree the Volta Lake resettlement process (Chambers, 1970; Kalitsi, 1973), which relocated approximately 80,000 people from 740 communities. Of the total, 69,000 chose to be resettled in 52 resettlement villages established by the Volta River Authority.

The remainder chose cash compensation. Well-conceived and well-executed social surveys laid the groundwork for preferences and needs; however, land clearing was delayed by difficulties in obtaining and maintaining heavy equipment. By 1964, only 8,000 acres of the targeted 54,000 had been cleared. The securing of tractors for mechanized cultivation--a necessary input for the modern farming envisioned--was also delayed, and the economic basis for the villages was weakened. When the lake filled in 1968, four years after closure, only 25,000 of the originally resettled persons still resided in the established villages. Only 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 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 some 60,000 people, 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 did not achieve 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.

Plate 3. Resettlement village one mile from the south shore, Volta Lake, Ghana.

The formation of new human communities is part of the resettlement process. This poses requirements and problems similar to those entailed in the colonization of new lands and, to some extent, to the relocation of slum dwellers in large cities. In developing countries, the formation of new communities following the relocation of large numbers of people has, in general, not been characterized by success. *Any nation which embarks on an over-all program of developing hydropower potentials must place high priority on developing the manpower, institutional, and administrative capabilities required for resettlement.* Past experiences should be evaluated in order to learn from successes and mistakes.

Although Lagler (1969) anticipated that the outcome of various approaches to resettlement in the major African man-made lakes (Nasser, Kainji, Kariba, and Volta) would provide useful comparisons for judging resettlement policies, the needed evaluations have not yet been undertaken. Kalitsi (1973) judged that it is still too early to draw conclusions concerning the Volta resettlement experience. In general, however, resettlement experiences have been disappointing. Scudder (1973) has concluded that the record in regard to the emergence of viable land-use and water-use systems is dismal, although resettlement agencies have been fairly successful in providing improved housing and social services.

b) *Key Questions and Data Needs*

1) *What number of people would have to be relocated and what are the cultural, social, and economic characteristics of their communities?*

2) *What is the nature and amount of food, livestock, and fish production and to what extent are they dependent upon natural productivity of the land or water as influenced by the annual flood cycle?*

3) *What are maximum feasible production levels under environmentally sound production technologies? What is the significance of possible food production to total national production and production goals, short-term and long-term?*

4) *Is suitable land available for resettlement? If so, to what extent are the soils and general physical environment comparable to community lands that may be*

flooded? Will land, crop, and livestock management needed in available resettlement lands require the application of technologies with which resettled people are unfamiliar? What technical and financial assistance measures are likely to be needed?

5) *Will resettlement result in a change in diet? If so, how, and what will be the consequences to human health? Will the resettlement site expose people to new diseases? Will migration result in the introduction of disease by relocatees? What measures will be needed to manage any new public health problems?*

6) *What is the probability of spontaneous migration of people to easily eroded watershed areas, and what preventive measures may be required? Are resettled people likely to be drawn by the lake's fisheries?*

7) *What are the alternatives to agrarian resettlement (e.g., fishing, moving to cities)? What measures would be required to effect a smooth transition and adjustment at the least financial and social cost?*

8) *What administrative and institutional capabilities are needed to guide resettlement, and what is needed to develop the needed capabilities?*

Demographic surveys should be made of the populations residing in all the alternative reservoir sites. These surveys should include rate of population growth to make possible projections of future populations, given the long planning time of large dam projects. The status of nutrition and health should be surveyed and important diseases identified. The possible effects of impoundment on habitats of disease vectors and the impact of resettlement on disease transmission should be examined in order to foresee potential disease problems and to estimate costs of management or control. The needs for developing water-supply alternatives to the man-made lake source should be assessed in terms of risk of exposure to waterborne diseases such as schistosomiasis.

To assess possible agricultural production losses as well as to project resettlement needs, surveys of present-land use and soils capabilities should be made. Estimates should be made of production potentials under improved management, the number of people who could be sustained from higher production, and the significance of potential production levels to regional or national agricultural production.

A comparison of the number of people present in the site to agricultural production and soils characteristics should be made to determine the amount of land of equivalent productivity needed for agrarian resettlement, assuming that types and levels of production would be similar to present ones. This requirement can then be compared to the amount and characteristics of lands available for resettlement purposes in order to determine the physical resource needs for resettlement. Available resettlement land must be inventoried and assessed as to general productivity, as well as suitability on cultural grounds. The analyses may conclude that more intensive or different kinds of production would be required, which would then indicate the need for well-planned technical and financial assistance. Such assistance could represent a major cost, and it should be estimated as accurately as possible in terms of money as well as manpower and time needed.

In the assessment of present production and of physical resource needs for resettlement, the resources of the river also should be studied. The contribution to nutrition and the cash economy of fishing should be quantified. The function of annual floods--if these occur--should be determined as it may affect soil productivity, fishing, and grazing. The unique benefits of annual floods would, of course, be lost on inundation. In upland resettlement sites, the additional resources needed to compensate for these benefits must be anticipated.

Since, in most instances, resettlement will require adjustments in production methods to a different natural-resources base, the needs for change, or innovation, must be assessed. The innovation or adaptation capacity of peoples to be moved should be evaluated by anthropologists and/or sociologists, and the result should be used to determine the assistance likely to be needed to evolve new forms of social organization and economic production. Rough cost estimates for this purpose should be added to the estimate of total costs of resettlement.

Lastly, an assessment of the possible farming benefits associated with drawdown of the man-made lake at the alternative sites should be undertaken. Such benefits compensate in some degree for the loss of well-watered alluvial soils. Drawdown farming could constitute one alternative for agrarian-based resettlement, particularly where dry periods cause water shortages.

The assessment of possible benefits from new fisheries which may develop in the proposed reservoir should be attempted. However, it will not be possible to achieve estimates comparable to those of crop production.

6. *Impacts below the Damsite*

Perhaps the most serious information gap in the study of tropical dams concerns downstream impacts resulting from changes in volume, sediment load, water quality, and seasonal hydrological cycle. To some extent, this information gap reflects a lack of basic knowledge of tropical estuaries that only recently has begun to be remedied. In general, estuarine productivity has been underestimated and the key role of estuaries in coastal as well as oceanic fisheries only recently defined. The importance of undertaking research and surveys in estuaries in order to assess adequately reservoirs proposed for rivers flowing into important estuaries cannot be overstated. The downstream impacts summarized next are organized around five major consequences: (1) reduction in sediment load, (2) reduction of peak flows, (3) increase and stabilization of minimum flow, (4) introduction of abnormal flows, and (5) alteration of water quality.

a) *Summary of Impacts*

Reduction in sediment load. The reservoir will trap most of the sediment being transported, thus causing outflow water to be essentially clear and sediment-free and with the potential to pick up available sediment downstream from the reservoir. This may lower the streambed; and it could even erode the foundations of the dam itself and possibly the foundations of other downstream structures such as bridges, bulkheads, and piers. The degree of possible scouring and damaging undercutting will be a function of the nature of the materials in the channel (possibly too large or cohesive to be moved), the channel slope, the channel cross section, and the quantity of water discharged. Delta formation at the mouth of a major river will be diminished to a degree that is a function of the reduction in the river's sediment load, possibly causing wave erosion that may damage ports and settlements. Mangroves may act to stabilize deltas but, over the long term, may be adversely affected by the cessation of sediment enrichment. In coastal zones affected by sediments redistributed from delta areas by coastal currents, reduction in sediment load will affect coastal erosion processes and possibly induce damaging current and/or wave erosion of coastal structures or lands.

Reduction of peak (flood) flows. Flood damage is lessened or eliminated, creating the possibility of land development and reclamation of poorly drained areas. However, special reclamation measures (e.g., poldering and drainage) may be needed.

Capacity for flushing, diluting, and transporting wastes and flushing away water weeds is lessened.

Seasonal groundwater recharge in floodplain areas ceases.

Cessation of annual floodplain inundation and enrichment by sediments will eliminate wildlife habitat, farming, and grazing influenced by this cycle.

Loss of irrigation from natural floods can be compensated for by irrigation, using water from the man-made lake, groundwater, or below-dam river sources. If so, demand for electricity generated by the lake to pump irrigation water will be potentially competitive with hydropower production goals and other uses of electricity, and the cost should be estimated and computed as a possible trade-off.

Seasonal spawning and nursery habitats in seasonally inundated backwater and flood-channel areas are eliminated. These areas may become stagnant, develop water-weed growth (which normally would be flushed out seasonally) and become habitats for disease vectors which seek quiet, stagnant water.

Reduction in the productivity of river water with a corresponding drop in fisheries productivity can be expected. This will, in part, be a function of the amounts of nutrients trapped in the reservoir.

Cessation of seasonal salinity fluctuation and nutrient enrichment in the estuary and offshore very probably will have an adverse effect on species which require less saline estuary waters during the annual flood and during some part of their cycle, either for breeding, feeding, or escape from predation. Changes in species abundance and composition may be drastic. Oceanic species which migrate to seasonally enriched coastal waters also may be adversely affected.

Relative stabilization of the brackish-water/freshwater interface in the river will develop. This may have possible adverse effects on sessile organisms adapted to a natural shift of the interface, such as the freshwater clam *Egeria radiata* in the Volta River. This species requires seasonal saline conditions for reproduction but less saline conditions for good growth. On the Texas coast (U.S.A.) stabilization of estuarine salinity levels resulting from streamflow regulation has favored the oyster drill, which normally is eliminated by seasonal flood and reduced salinity. This has been detrimental to its prey, the commercially important oyster.

The loss or decline of estuarine and downstream river fisheries could be compensated for to a degree by the creation of new fisheries in the man-made lake, as has taken place on Volta Lake. The trade-off could be measured in terms of protein; however, fishing efforts will also reflect market demand. Certain estuarine species, or estuarine-dependent species such as shrimp, may be more valuable than freshwater species, and this economic consideration should be assessed.

Diminished flow may create a perennial, well-aerated, running-water habitat suitable for year-round breeding of arthopod vectors of human disease such as *Simulium* sp., transmitters of river blindness, and *Anopheles maculatus maculatus* and *A. minimum minimus*, vectors of malaria in parts of southeast Asia.

If lowering and relative stabilization of the groundwater level result, changes in hydromorphic soils will occur in low-lying areas. Soils rich in iron because of reducing conditions may become lateritic upon drying out. Changes in aquatic and riparian vegetation will take place. Flood-tolerant species presently abundant may increase or decrease depending upon their competitive advantage with other species. Water weeds may spread.

Increase and stabilization of minimum flow. Water supply for agricultural, domestic, and industrial uses is stabilized. Better dilution and transport of waste are provided during the dry period of minimum flow. Navigation may be benefited by more predictable flow and depth.

Introduction of abnormal and variable flows caused by project operation. High flows to create flood-control space in reservoirs could flood downstream, low-lying croplands and resettlements which could be reclaimed from the floodplain. Periodic discharges for peak power generation or control of disease vectors could have similar consequences, although of lesser magnitude. High discharge rates could spill hypolimnetic water (e.g., water from deeper portions of a lake) and introduce abnormally high levels of iron and manganese that have been concentrated by reducing conditions in the hypolimnion, with adverse effects on domestic and industrial uses and on aquatic life.

b) *Key Questions and Data Needs*

1) *What would be the impact of regulated flow and reduced sediment load on erosion along the river, on the delta, and along the coast? Would engineering structures and settlements be adversely affected? What measures would be needed to control erosion damage and at what cost?*

Several researchers have addressed the problem of how to predict riverbed degradation below dams following impoundment (Komura and Simmons, 1967; Hales et al., 1970). Mathematical formulae are employed for this purpose. The needed data include knowledge of particle size and distribution before operation of bed materials (as distribution curves), probable outflow release rates, and channel cross sections. These data may not be available for site-selection assessment and may not be necessary. Also, at the design stage, engineering solutions can be applied to stabilize stream beds immediately below dam structures. However, a rough appreciation of scouring potential may be obtained by sampling stream-bed sediments and comparing these to sediment loads during times when river flow is similar to probable outflow volume following impoundment.

Reconnaissance geomorphological and sedimentological surveys of deltas and adjacent coastal zones can assist in assessing consequences of reduced sediment loads in these zones. Sequential aerial photography, if available, can be used to great advantage for this purpose.

2) *How would land and water usage in the floodplain be affected by regulation of flow? What are the productive capabilities and present production levels of floodplain areas that would be affected? If flood-control benefits are assumed in the project, what are the corresponding production potentials, and what is the estimated cost of achieving these potentials?*

Present land-use types and practices in the floodplain should be surveyed and mapped with the aid of aerial photographs, if available. The value of present and potential production, without flow regulation (e.g., without the dam) should be assessed. The cost of achieving improved levels of production without the dam should be estimated and compared to the cost projections for achieving improved production following dam construction, flow regulation (and irrigation if planned), and land reclamation.

If flood-control benefits are assumed in the project, surveys and evaluations of soils capabilities and reclamation possibilities would be integral to the site-selection studies. Also, it is assumed that appropriate hydrological and water-quality data would be obtained as a matter of course where flow regulation is projected to generate water-use benefits. The laterization possibilities of tropical hydromorphic soils will require special attention.

Surveys for the design of irrigation and drainage systems and of community water-supply and wastewater systems should take into account the needs and requirements for controlling aquatic weeds and habitats of disease vectors such as malarial mosquitoes and the intermediate snail hosts of schistosomiasis. McJunkin (1970) has reviewed engineering measures for the control of schistosomiasis in water-distribution and drainage systems. The status of and practices for schistosomiasis control in various water-development projects around the world were recently reviewed at an international symposium (Miller, 1972, p. 83). Shiff (1973) reports that the snail control chemicals "Frescon" and "Bayluscid" do not appear to affect adversely plankton and other invertebrates, although most species of fish are sensitive to both compounds, especially in still water.

The probable costs of schistosomiasis control and surveillance--which may include concrete lining of ditches, molluscicide application, chemotherapy, and protected water supplies--should be estimated. Drainage and prevention of salination of soils also require special surveys, and this important aspect of water resources development has been the object of a major publication (FAO/UNESCO, 1973).

Wildlife and habitat values in deltas with significant wildlands should be assessed, and the impacts of flow regulation on these values should be estimated.

3) *What changes in physical and chemical characteristics of the water can be expected?*

These characteristics should be measured at least four times in one year at the damsite location. Estimates of the reduced sediment load should be translated into possible changes in water clarity, which in turn would influence primary productivity (by allowing sunlight to penetrate deeper into the water). Changes in water temperature as influenced by reservoir-water temperatures would mainly affect the water near the outflow points of the proposed damsite and would not be important to assess. In stretches farther downstream, temperatures could increase because of smaller volume. Present minimum-flow temperatures may be indicative of future temperatures during periods with similar temperatures. The possible significance to aquatic biology should be estimated. Phosphorous, nitrogen, potassium, manganese, and other minerals may be trapped in reservoir waters, sediments, and biota, but this cannot be forecast accurately. These minerals should be measured in the water below the proposed damsite. In Volta Lake, an estimated 41,000 m.t. of minerals are released annually in the outflow; an estimated 16,000 m.t. are trapped in water weeds and, in part, cycled to herbivorous fish. The amounts trapped in sediments and other biota have not yet been estimated. In drier regions, where shallow reservoirs are proposed, the possibility of concentration, by evaporation, of mineral salts should be assessed in terms of likely effects on quality of outflow water.

4) *What is the nature, quantity, and socioeconomic importance of present fisheries, shellfish, and other aquatic resources of the river and estuary? What alternatives are there for lost production? What is the value of the estuary for high-seas fisheries? How would these values be affected by flow regulation and what are the estimated costs in terms of gross production, protein, and monetary value in the short and long term?*

Data obtained on the physical and chemical characteristics of river water and on sediment load, mentioned above, will contribute to the assessment of river and estuarine productivity. Both present and potential production from fisheries and other aquatic life should be assessed. Existing data, interviews, and observations can be employed to determine present production. The role of aquatic protein in local diets should be determined by sample interviews. In order to assess probable impacts, the life histories and aquatic ecological determinants of presently harvested species should be determined and related to expected changes in hydrology and water quality. Requirements for spawning, breeding, nutrition, and migration should be established for species in both freshwater and estuarine areas (some species may occupy both areas at different stages of the life cycle) by means of sampling and analysis. Field or laboratory research may be required to determine experimentally the possible impacts on important species of expected changes in the flow and productivity regimes.

For rivers affecting important estuarine fisheries, data should be collected at several locations in the estuary for the purpose of assessing likely changes in production and productivity. A number of stations should be established to sample water quality (especially salinity), sediments, and biota. Samples should be taken at approximately monthly intervals and timed for consistency in relation to tides. The life histories of major commerical species and their food sources should be related to the normal flux of estuarine water quality in order to provide a baseline for assessing the possible impacts on fisheries of altered water quality. If juveniles or larvae of species important to coastal or high-seas fisheries are found, the role of the estuary in the conservation of these fisheries should be assessed, with special attention given to the impacts on these species of altered estuarine hydrology and water quality.

To determine potential fish and other production in either rivers or estuaries, experimental catches should be made and compared with local catch data. Efficiency of fishing gear and methods should be evaluated. The possibilities and beenfits from increased catches should be estimated.

These data should be developed so as to provide a quantitative measure of present and potential aquatic resources, an assessment of their socioeconomic importance, and an assessment of the importance and--to the extent possible--magnitude of likely impacts resulting from upstream impoundment and flow regulation. Estimated production losses should be compared to possible new production in the proposed man-made lake, using as criteria both nutritional (protein) and monetary values.

5) *Would flow regulation create favorable habitats for undesirable aquatic plants and/or human disease vectors? If so, what control measures are possible, and how much would these cost?*

Aerial and ground reconnoiters of low-lying wetlands and quiet waters in the floodplain such as oxbox lakes and flood channels should be made to determine the extent and likelihood of the water-weed and disease-vector problem. If aerial photographs are available, wetland areas can be initially identified from typical vegetation associations. Infrared imagery clearly shows wet areas because water absorbs heat energy (e.g., on the red end of the spectrum). Imagery from the Earth Resources Technology Satellite (ERTS-1), if available, can be most useful for this purpose, since near-infrared imagery has been obtained. Aquatic biota in wetlands during low water (dry season) can be viewed as indicative of conditions likely to persist after dam construction and flow regulation, and conditions in shallow channels with low rate of flow are analogous to those of irrigation and drainage canals. Aquatic biota in existing canals should be examined.

The cost of drainage, if judged necessary, should be estimated.

6) *What would be the impact on downstream land and water uses of periodic high-volume spills from the reservoir?*

The probabilities of high-volume spills to make flood-control space in the reservoir should be projected, using rainfall and streamflow records. However, volume of spills would be dependent on, among other factors, height of dam, size of reservoir, and operating level, none of which would be established until the design phase. Also, an assessment of the extent of influence of a high-volume spill (if it could be quantified) would require fairly detailed topographic information (e.g., contour intervals of 1 meter or less) of potentially affected floodplain areas. These data may exist for some sites that have been better studied but not for others. However, the relationship of the probable need for high-volume spills and of plans for floodplain land uses should be examined in a preliminary way and taken into account in site selection.

7. *Organization and Survey Procedures for Alternative Sites*

The various elements recommended to be studied and discussed in previous sections are summarized in Table 3. Time and money can be conserved through careful planning and coordination of the individual studies needed to generate data for the site-selection assessment. The entire process can be divided into the following components:

1) Collection of all available aerial photographs, maps, and data on the alternative reservoir sites and their catchment areas, including ERTS satellite photography.

2) Preparation, if necessary, of 1:50,000 scale orthophotographic topographic maps of the reservoir sites using existing 1:60,000 scale or new aerial photography. If topographic maps at this scale already exist, the aerial photographs employed in their preparation should be used to construct controlled aerial photo mosaics at the same scale. The shoreline at various levels of operation should be traced on these maps.

3) Installation of observation stations and instrumentation in the proposed reservoir site, tributaries, and downstream estuarine areas (and coastal waters if relevant) for a one-year period of observation. Instruments recommended to be installed are sediment samplers, evaporation pans or lysimeters, rain and temperature gauges, and portable seismographs (if the region is known to be seismically active).

4) Review and analysis of existing data.

5) Field surveys.

6) Evaluation of field data.

7) Preparation of environmental assessments with recommendations for site selection and for further studies and analyses of selected sites.

The assessment effort could be organized as a single operational entity reporting to an appropriate ministry or high-level planning agency. From start to finish the assessments may require between 18 months to two years. Because of the strong influence of seasons on climate, water quality, aquatic biota, and river and estuarine resources, observations of these aspects must be made over at least a one-year period in order to develop an adequate data base for assessment.

By conducting assessments on a number of alternative sites simultaneously, economies in time and money can be achieved, especially with respect to the logistical support for periodic observations at sampling stations and the

Table 3 Summary of environmental considerations for the assessment of alternative dam and reservoir sites

Consideration	*Study elements*	*Methods and tools*
The influence of climate, geology, vegetation, and land use in the reservoir catchment on general reservoir productivity, sedimentation, and watershed management. (Consideration for site identification.)	Regional survey and evaluation of surface geology, geomorphology, natural vegetation, and land uses as these affect runoff and water quality. Evaluation of land-use management need in the catchment.	Review of existing maps, data and surveys. 1:60,000 scale aerial photographs and 1:250,000 or larger scale topographic maps. Field and aerial reconnaissance of catchment.
Seismic hazards.	Evaluation of regional tectonics and seismic history. Identification of active or potentially active faults in vicinity of damsite. Seismic observations.	Review of existing knowledge. Mapping of major fault planes and earthquake epicenters. 1:60,000 scale aerial photographs and 1:250,000 (or larger) scale topographic maps. Portable seismographs.
Loss of reservoir capacity from sedimentation.	Determination of reservoir-site topography and morphology. Measurement of suspended sediments in reservoir tributaries and assessment of probable sedimentation rates in the reservoir from these and direct runoff.	1:50,000 scale orthophotographic topographic maps of the reservoir site, with at least 50-foot contour intervals. One year of sediment sampling in reservoir tributaries, with integrated sediment samplers.
Loss of reservoir capacity from evaporation.	Measurement of potential evaporation rates at different seasons for the projected reservoir surface, at different levels (i.e., surface areas).	Analysis of existing meteorological data. Observations, over at least one year, of evaporation, rainfall, and temperature. 1:50,000 orthophotographic maps of the reservoir site with delineation of shoreline at different stages of operation.
Loss of reservoir water to subsurface runoff.	Assessment of subsurface and surface geology in reservoir site, affecting seepage and rate of loss to underground aquifers. Estimate of potential volume of subsurface runoff after impoundment.	Photogeological and field surveys. Analysis and monitoring of existing wells over one-year period.
Flooding of rivers and natural forests resulting in species and habitat losses, problems in navigation and fishing, and potential benefits and problems for the future man-made lake.	Surveys of terrestrial flora and fauna in the reservoir site and of riverine flora and fauna in the reservoir site and upstream, with emphasis on adaptable weeds, fish, and disease vectors.	Botanical and zoological surveys. Measurement of extent and height of natural forests and comparison to reservoir shoreline and potential navigation and fishing activities.

Consideration	*Study elements*	*Methods and tools*
Loss of archeological sites and remains.	Estimates of research and salvage needs in the reservoir site. High-level assessment of the societal value of existing sites and remains.	Review of existing knowledge, aerial photointerpretation and exploratory ground surveys. Exploratory excavations possibly needed. Consultation with high government officials, scholars, educators, and religious leaders on known or suspected remains to determine value to society.
Flooding of human settlements and farmlands.	Demographic, socioeconomic, and health surveys of potentially affected people. Examination of human disease ecology. Assessment of adaptive or innovative potentials of the potentially affected people.	Review existing data and supplement with census and interviews. Health and nutrition surveys with emphasis on river resources in the diet. Evaluation of past experience in innovation.
	Determination of present and potential productivity of existing and potential agricultural lands, at different levels of management.	Reconnaissance soils surveys and land-capability evaluations of presently cultivated and unused agricultural lands. Extrapolation of potential productivity levels from experiences in similar soils/climate combinations.
	Determination of physical resource and assistance needs for people if resettled.	Inventory and evaluation of physical resource base (soils, climate) of available resettlement sites. Comparison with resource base used by people in reservoir site in order to determine need to learn new management and production methods.
Alteration of downstream hydrology and aquatic ecology with beneficial as well as adverse impacts on estuarine life and productivity.	Survey of present land uses and habitat values in seasonally inundated floodplains and of floodwaters.	Land-use mapping with existing maps and aerial photographs or new 1:60,000 scale air photos and mosaics constructed from these. Interviews with floodplain farmers and ranchers. Analyses of selected soils before and after flooding. Aerial reconnaissance during the flood period to delimit extent of influence of floodwaters.

Surveys and evaluations of present river and estuary productivity and harvested species. Estimates of likely impacts of altered river-flow on this productivity and production, resulting from changes in flow and water quality.	Sampling stations for water quality and aquatic biota in the river and estuary. Experimental fishing. Observations of the influence of seasonality of river-flow on aquatic biota (e.g., on spawning, breeding, nutrition).

mobilization of field workers. If rainy periods limit ground travel to certain months, several field survey teams may have to be mobilized at the same time.

It is clearly desirable to conduct simultaneous assessments of a number of alternative sites that have been preliminarily selected on the basis of equivalent hydropower-generating potentials. In this way, planning and decision-making can proceed with a minimum of delay.

In the interpretation of the various impacts and their costs, the services of an economic analyst--preferably an economist with experience in the cost-benefit analysis of hydropower projects--should be employed. All costs which can be expressed in financial or economic terms should be incorporated into the preliminary economic analyses of the alternative sites. Engineering solutions suggested by the assessments of problems such as sedimentation, water weeds, impediments to fish migration, and erosion should also be converted into costs.

Finally, the preliminary assessments recommended here for the purposes of site selection may uncover the need for more detailed examination of environmental, social, and economic considerations. The methodologies for environmental assessment at various levels have not yet evolved to the point that concrete guidelines can be set forth. However, when a dam project advances to the prefeasibility stage in which information is to be obtained for the justification and planning of technical and economic feasibility studies, the assessment of the various environmental considerations set forth in this section should be continued and expanded. The findings of the preliminary assessment will be the point of departure in defining the objectives and scope of additional assessment studies.

8. *Satellite Photographs for Reconnaissance Level Assessments*

For large or little-known regions, imagery from the ERTS I satellite can be used to good advantage for obtaining an overview of the land-cover and drainage characteristics of watersheds, floodplains, and deltas. Prints of ERTS I imagery can be obtained on a 23 mm by 23 mm format similar to that of standard aerial photographs. Each image or photograph covers a square approximately 185 kilometers on a side. On the 23 mm by 23 mm format the image is approximately at the 1:1,000,000 scale (1 mm equals 1 km). Enlargements to a scale of approximately 1:250,000 are possible.

A Multispectral Scanner Subsystem obtains images of the earth on four different spectral bands--near infrared (two bands), red, and blue-green--as the satellite orbits the earth. Thus, four photographs exist for the same area. On infrared image photos, water is black and vegetation very light; thus, stream patterns, flooded areas, and wetlands show up very clearly. This band can be most useful in the reconnaissance study of deltas, floodplain areas, and areas with waterlogged soils. On the green band, vegetation appears dark and characteristics such as density of cover

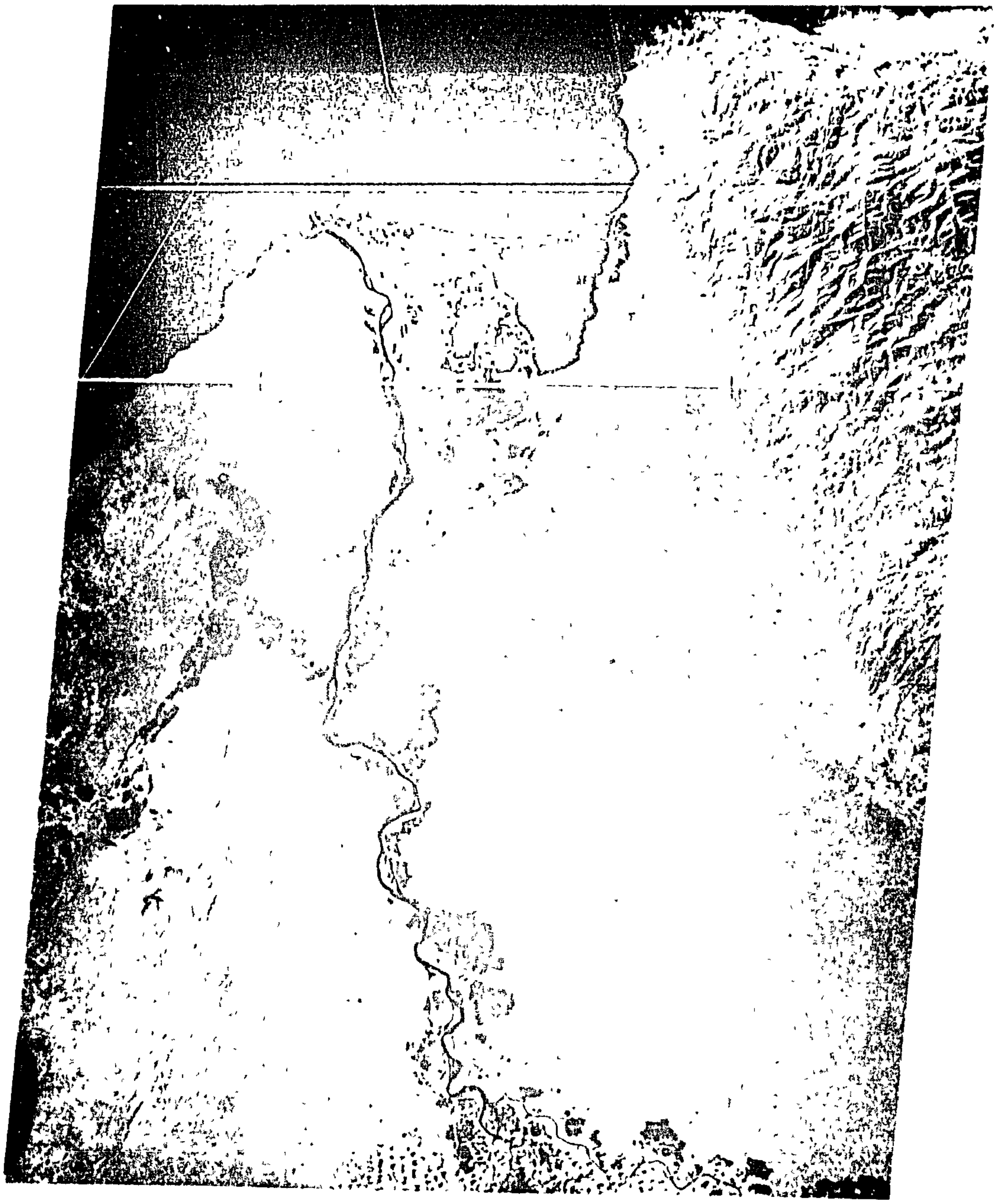

Plate 4. ERTS-1 satellite image of coastal plain. In this near infra-red image of the Magdalena River, Colombia, South America, water stands out clearly in black, since it absorbs longwave radiation.

can be identified; and, with ground checks, vegetation associations can be mapped. The imagery also is useful for mineral exploration, geological mapping, detection of coastal currents and changes in coastlines, mapping patterns of urban development and agricultural land use, and other features (Freden and Mercanti, 1973).

ERTS I imagery is available for most of the major landmasses of the world and large portions of the oceans. The satellite orbits the earth 14 times a day and can cover the entire globe once every 18 days. Images began to be recorded in July 1972 and continued until approximately April 1973. After that date, the securing of imagery of areas outside the U.S.A. has been erratic because of problems in image recording and storing in the satellite. Imagery over the U.S.A. is transmitted directly to ground stations, while imagery taken of areas outside the U.S.A. is recorded and stored on tape for later transmission to ground stations in the U.S.A. Outside the U.S.A., only Canada and Brazil have ground receiving stations.

ERTS I photography can be obtained from the EROS Data Center, Sioux Falls, South Dakota, 57198, U.S.A. The availability of coverage for the region of interest should be requested. The geographical coordinates should be noted, and the EROS Data Center will respond by sending a computer-listing of all available imagery for the area, including notations as to image quality and extent of cloud cover if any. The cost of a single 23 mm by 23 mm print is approximately $1.75.

B. ASSESSMENT OF HYDROLOGICAL AND BIOLOGICAL IMPACTS FOLLOWING DAM CLOSURE

1. *General Considerations*

Once a damsite has been selected and the decision made to proceed with design and feasibility studies for its construction, an assessment of hydrological and biological impacts that are likely to take place in the impoundment is justifiable and necessary. The assessment should be an integral part of the feasibility stage of a dam project. It will produce information needed for the management of fisheries and other resources of the man-made lake and for the management of problems such as water weeds and human disease that may be associated with its formation. With such an assessment, costs and benefits of these aspects can be more precisely determined and incorporated into the project financing. Thus, the main objectives of hydrobiological impact assessment at this stage are (1) to obtain data needed for the management of productive resources and potential problems and (2) the more precise definition of possible impacts for improved cost-benefit analysis and the projection of management needs and costs. The data collection and analysis related to the assessment can be viewed as an investment in the management of the future man-made lake.

The management of fisheries, water weeds, navigation, recreation, and other aspects will be influenced in a critical way by hydrobiological changes as the man-made lake develops and matures ecologically. For example, flooding commonly releases large quantities of mineral elements from the soil and vegetation, thus enriching the water. This may result in high fish production in initial years, and with advanced planning this resource can be exploited. However, total fish production eventually will become relatively stabilized at a lower level. This can be explained by the declining productivity of the lake's waters as the lake matures. Preimpoundment studies can help assess this phenomenon. If a fishing boom is likely to be followed by a bust, it should be anticipated and the possible social and economic consequences should be taken into account.

Independently of productivity levels, reservoir stabilization and attainment of relative maturity will be characterized by more complex food webs and more trophic levels (Figure 2). These characteristics will be unique to a particular reservoir and not totally predictable; therefore, future production of commercial fish species will be difficult to forecast accurately, although rough estimates of total fish biomass are possible.

Forecasts of the potential magnitude of the human disease problem also may be difficult. Vectors can be identified but the role of natural regulatory mechanisms in their control is not easily predicted. Basic information on the life history of vectors (and associated parasites) may be incomplete, but such information can be obtained and the importance of disease vectors defined. With this information it may be possible to control the human-exposure factor to some extent. Changes in personal habits and activities so as to minimize human exposure or interrupt the transmission cycle can be promoted; hazardous locations can be posted and avoided; and quarantine programs can be devised in order to interrupt transmission or retransmission from areas outside the reservoir basin. These and other considerations are addressed in the summary of impacts and the assessment guidelines that follow.

The impacts described are roughly patterned after the Volta Lake experience, in which initial high productivity dropped to a lower level approximately six years after closure. In man-made lakes, which may stabilize at a relatively high level of productivity, the events that characterize initial filling (phytoplankton blooms, depletion of oxygen, explosive growth of water weeds) may persist during the life of the reservoir.

Hydrological and biological impacts can be viewed in various ways--in terms of the major physical and biological components of the aquatic system, in terms of lake limnology, or in terms of changes over time. Here they are described for three periods in the formation of the lake: (1) as the lake begins to fill, (2) during filling (which may take four or five years for large projects), and (3) during the period of stabilization after filling to capacity.

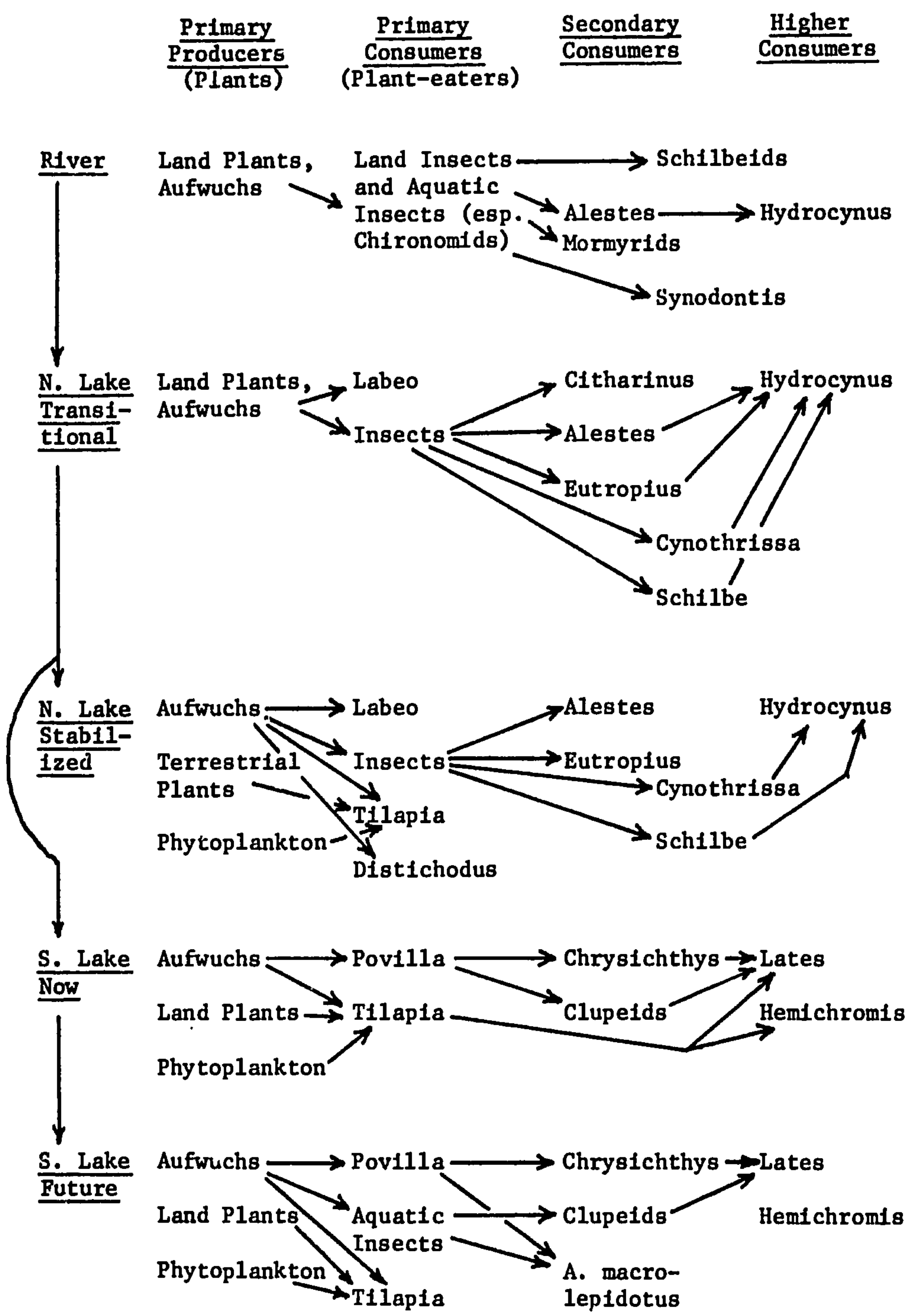

Figure 2. Lake developmental sequence: simplified typical food chains, Volta Lake.

a) *Summary of Impacts*

Period of rapid flooding after closure. The period between dam closure and attainment of projected reservoir water level is the stage of maximum instability (SCOPE, 1972). Highest instabilities occur during initial flooding and become buffered over time as the reservoir watermass grows, the rate of flooding slows, the available nutrient store in drowned biota is depleted, and lacustrine limnology develops.

There is rapid release of nutrients to the water from riparian vegetation (leaves present extensive, easily attacked surfaces), detritus and nutrient-rich soils of levees, floodplains, and lower terraces. Increase in the levels of nitrate, phosphate, and potassium occurs. Oxygen is necessary for the release of elements by biological action; thus, oxygen levels may drop precipitously following submergence, even though lake water is initially well supplied with oxygen from river inflow. The water body may then emit the rotten-egg smell of hydrogen sulfide, generated by sulphate-reducing bacteria typically associated with anaerobic (oxygen-poor) conditions.

Water is initially turbid, and the euphotic zone (in which sunlight penetrates) is initially shallow. Explosive and successive blooms of algae are likely, and these are accompanied by pronounced fluctuations in levels of dissolved oxygen. Blue-green algae are likely to predominate in early stages. An increase in the number of algal species over that of the river can be expected. Riverine life that cannot adapt is killed or excluded. Algae and adapted macrophytes (e.g., primary producers) initially are favored over vertebrates such as fish (e.g., primary, and secondary, and higher consumers). Certain fish are inhibited by fluctuations in dissolved oxygen; mass die-off of certain species may occur.

Rate of flooding slows as mainstream and tributary gorges fill and water surface increases. Microbiological and chemical decomposition of the softer parts of vegetation continues to release nutrients, but over time the rate of release slows as softer parts such as leaves are destroyed. A proportionate reduction of nutrient additions from soil and vegetation may occur as the reservoir watermass increases relative to the soil surface and vegetative biomass being submerged by rising water.

Oxygen contribution from tributary inflow decreases in relative terms as the watermass increases. But as algal blooms damp, following decline in available nutrients, less available oxygen will be used in the biological decomposition of dead algae. Thus, oxygen levels in the surface water may increase as biological production and consumption come into balance.

Stratification of water temperature and chemistry begins as the water deepens. Anoxic conditions are likely to develop in the deeper hypolimnion. Anaerobic decomposition may take place and result in hydrogen sulfide gas. Nutrients that may become trapped in this stagnant hypolimnion probably will include iron, which is mobilized by reducing conditions.

The relatively rich nutrient status of oxygenated surface water continues to favor plankton production and adapted macrophytes, especially free-floating types (e.g., *Pistia stratiotes*, *Salvinia* spp., *Eichhornia* spp.) but also rooted emergents (e.g., *Vossia* spp. throughout Africa). Weeds may form floating islands (sudd) drifted by wind. They can become lodged in the branches of bushes and trees left standing in the reservoirs or may be swept to weed-free areas where they establish colonies. Water-weed beds and sudd may become good habitats for arthropod and mollusc vectors of human diseases. "Aufwuchs," consisting of plants and small animals associated with submerged vegetation and water weeds, increase and provide food for fish.

Fish biomass increases, and conditions initially favor adapted planktivorous, herbivorous, and omnivorous fish (primary and secondary consumers) whose production may increase dramatically as oxygen levels improve. Facultative feeders are favored over obligatory feeders. Insectivorous fish, which may have been dominant preimpoundment fish in both species and abundance, may adapt to the reservoir but a change in species dominance is likely. Maximum fish biomass may be produced during this period. Large fish harvests may be possible if fish biomass and composition include acceptable food-fish and if adequate fishing methods are employed. Benthic (bottom) feeders and carnivorous predators eventually increase in response to the increasing food supply. Total fish biomass may drop as carnivores become established, in part because of the energy loss associated with this additional step in the food chain. Complex food webs develop and trophic levels increase.

As the reservoir approaches its projected level, seasonal influences on lake productivity become manifest (Volta Lake seasonal cycles are shown in Figure 3).

Projected capacity and water level attained. The physical, chemical, and biological character of a lake reflects the influence of climate and seasonal changes in rainfall, temperature, insolation, wind action, and runoff (Figure 3). Peaks of phytoplankton production generally coincide with months of greater insolation, water clarity, and nutrient levels, possibly following the rainy months and reservoir flood (as in Volta Lake).

As the lake stabilizes, recently flooded vegetation and soils will continue to contribute nutrients. An alternately flooded and exposed drawdown zone becomes established and will be extensive in foreshores with shallow gradients. Wave action begins to erode finer sediments from shore, adversely affecting drawdown-zone farming. Natural succession of macrophytes in the drawdown zone (Table 4) probably will result in the spread of grasses, sedges, and herbs, with a probable dominance of rooted emergents adapted to fluctuating water level (e.g., *Vossia* spp. in Africa). The growth of free-floating species (e.g., *Eichornia* spp.) may be curtailed by

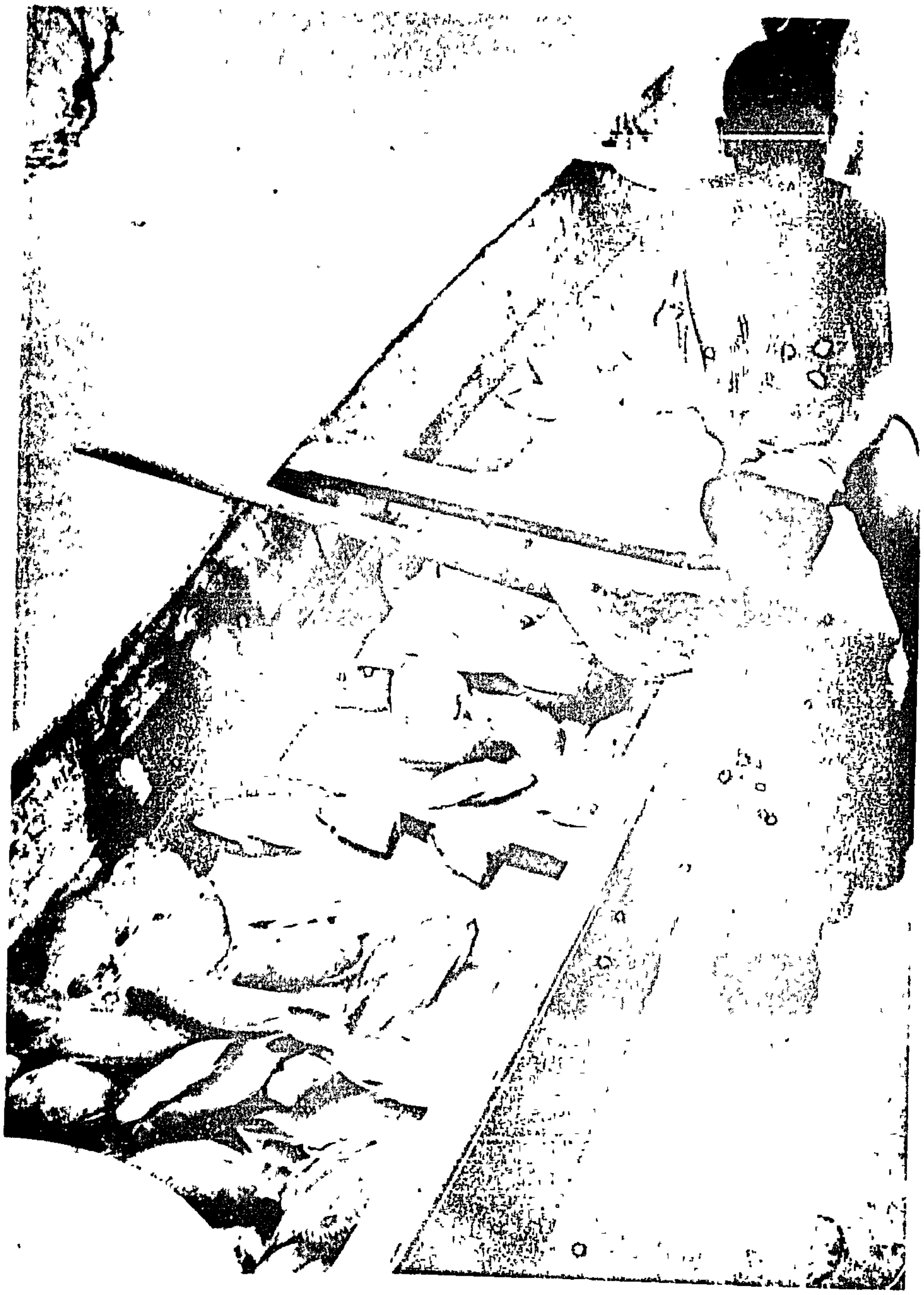

Plate 5. Fish catch, Volta Lake. Watercraft have been slow to adapt to lake conditions. But river fishermen responded quickly to the large catches possible on the lake. Catches have been more than double the preimpoundment estimates.

Figure 3. Seasonal cycles on Volta Lake.

	MONTHS													
	1	2	3	4	5	6	7	8	9	10	11	12	1	2
Precipitation		minimum				MAXIMUM	reservoir		floods	minimum				
Winds		cool N. Harmattan					Cool moist southerlies					cool northerly		
Water temperature		lower								HIGHEST	lower			
Stratification and mixing of water column	MAXIMUM MIXING					MAXIMUM MIXING				MAXIMUM Strati- fication				
Benthic fauna	deeper (10 m)			more shallow (5-7 m)		deeper				more shallow		deeper		
Plankton production	decreasing			maximum recorded in some years			low			HIGHEST				
Invertebrate production							HIGHEST esp. in littoral							
Macrophyte growth							Increase, mainly in the drawdown, littoral							

Table 4 Comparison of major changes in aquatic weeds during the first 10 years in Lake Kariba and Volta Lake.

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	Increase in sudd	Decrease in sudd
5	--	Development of grasses, sedges, and herbs in drawdown area
6	Decrease in sudd; *Potamogeton* appears	Spread of grasses, sedges, and herbs in drawdown area
7	Development of grasses, sedges, herbs in drawdown area	*Vossia* and *Polygonum* increase in drawdown area
8	--	*Vossia* continues increase; *Polygonum* stabilizes
9	No dramatic changes	No dramatic changes. New submerged plant (*Potamogeton*) appears
10	New submerged plant (*Lagerosiphon*) appears	--

Sources: Mitchell, 1969; Pierce, 1971; observations by J. D. Reynolds in 1973.

a drop in water-nutrient status, resulting in cessation of spreading and a density reduction as occurred on Volta Lake. However, if runoff is rich in mineral nutrients, weeds may continue to spread over the surface of the reservoir, as occurred in Lake Kariba.

Total fish production declines. Fish that are primary and secondary consumers and responsive to fluctuations in primary production may show seasonal peaks in biomass. Spawning and breeding of some species are likely to adapt to drawdown zone during reservoir flood. Periphyton on standing vegetation will constitute a relatively stable food supply but may decline on standing vegetation and increase on macrophytes (water weeds). Benthic feeders and predators become better established and probably will increase in relative dominance or biomass. In larger reservoirs, pelagic primary consumers and their predators become established (e.g., in Volta Lake, the insectivorous clupeid *Pellonula* and its predator *Lates*).

Food webs and trophic levels continue to evolve and species diversity increases. In deeper water near the dam, tropical lacustrine characteristics such as stratification of temperature and chemicals become evident. In shallower water, quasilacustrine and quasiriverine limnology develop. Deeper (hypolimnetic) water becomes more or less permanently anoxic and traps minerals, including iron and manganese. Anoxic conditions in the hypolimnion inhibit biological decomposition of inundated terrestrial vegetation. In the lacustrine portions of the reservoir, mixing of water--and therefore of depth of dissolved oxygen and of nutrient concentrations in the water column--becomes a function of wind action and internal waves.

Deltas begin to form at tributary mouths and finer sediments are deposited in quiet or deeper waters. Phosphorus may be trapped in finer sediments.

b) *Key Questions and Data Needs*

The preimpoundment data needed to answer most of the questions later also will be needed to guide the management of the lake's resources following dam closure and formation of the lake. Thus, data collection will be the first step in a long-range monitoring effort for lake management.

The starting point for assessing potentials for fisheries, water weeds, and even human disease is productivity; more specifically, primary production--the conversion of inorganic matter to organic matter through photosynthesis. Photosynthesizing organisms include unicellular algae as well as larger macrophytes such as water lettuce (*Pistia stratiotes*). Potential fish productivity and water-weed growth are largely determined by the mineral cycle and its role in primary production, especially in tropical man-made lakes. Whether or not desirable or undesirable species of fish and plants will become dominant in a reservoir will depend upon the response of preimpoundment flora and fauna to changes in habitat conditions and on likely primary production levels in the lake.

Seasonal influences are as important to biological production in the reservoir as they are to reservoir storage and power generation. Thus, research on primary production and related biological events over at least a full year's cycle is needed in order to arrive at an acceptable assessment. Further, the collection of baseline data for assessing water quality, the mineral cycle, and primary production should be undertaken following design criteria for a long-term monitoring effort, which should be integral to any future reservoir.

The research programs undertaken on the hydrobiology of Volta Lake (Obeng, 1973) and Lake Kainji (Visser, 1970) are indicative of the content, scope, and duration of studies required to assess impacts and guide management of a future tropical reservoir. Visser has itemized some of the major lines of research needed to understand the aquatic environment of the man-made lake. His rather detailed research agenda is presented below to provide an idea of the general structure of an *ideal* program (Visser, 1970, pp. 14, 15):

I. Physical measurements:

(a) investigation of the water budget leading to the main water body: rates of flow of in- and out-flowing streams and rivers; rate of atmospheric precipitation, losses by evapotranspiration, contribution or loss with respect to groundwater.

(b) investigations on water movements in the pond or lake; rates of inflow and outflow, variously induced currents.

(c) investigations on solar and thermal radiation and transparency as functions of depth; spectral composition and integration, intensity, periodicity.

(d) investigations on temperatures and heat flow in the system.

II. Chemical measurements:

(a) sources of the organic and inorganic matter in the ecosystem. Investigation of the contribution by precipitation (rain); gases and dust from the atmosphere; dissolved and flocculant organic and inorganic matter, silt, etc., carried by inflowing rivers; chemical compounds in the groundwater; release, fixation, and accumulation of organic and inorganic compounds by the substratum; contribution by the biomass, sewage, and pesticides.

(b) analysis of chemical components: major elements such as C, N, O, P, S, Na, K, Ca, Mg, Fe, Si; minor elements such as Mn, Cu, Zn, Co, Mo; dissolved gases such as O_2, CO_2, NH_3, CH_4, H_2, H_2S; organic compounds and their derivatives, amino acids both in the free form and incorporated in peptides and proteins, organic acids, lipids, purines, pyrimidines, enzymes, carotenoids, vitamins, growth factors, pheromones, pesticides, herbicides, fungicides, insecticides, pollutants, fertilizers, petroleum products.

III. Biological analyses:

(a) species inventory, abundance and distribution of species; distribution of neuston, plankton, nekton, adhering organisms (aufwuchs), and benthos in the littoral, limnetic, and profundal zones and in the substratum.

(b) rates of metabolism: photosynthesis, respiration.

(c) standing crop: producers, consumers, decomposers.

(d) amount of biomass being removed per unit time by: harvesting, migration, death, predation by terrestrial animals, outflow, fixation by sediments.

(e) amount of biomass being formed per unit time and volume or area: rates of turnover.

Techniques for the collection, analysis, and interpretation of data for primary productivity, secondary productivity, fish productivity, and fish production are under continuous refinement, but generally accepted methods are in use and are contained in manuals such as those of the International Biological Programme (Ricker, 1971; Golterman, 1971; Vollenweider, 1969; Edmonson and Winberg, 1971). Details are not elaborated below for the various methods required because it is assumed that the data will be collected and analyzed by qualified scientists. Qualified scientists should also participate in the design of the data collection and analysis effort.

At a minimum, four categories of hydrological and biological data are needed in the preimpoundment assessment study: (1) reservoir morphology and topography, (2) tributary and rainwater characteristics, (3) aquatic biota, and (4) river fisheries.

Reservoir site morphology and topography. These data are essential to assessing the probable limnological conditions of the future reservoir, estimating the area/capacity curve at various water levels, assessing the various problems and potentials of the drawdown zone, and determining navigational possibilities and requirements. Modern mapping methods should be employed, using a map scale and type designed for the purpose. Orthophoto maps at 1:20,000 scale and with 10-ft contours (or a suitable metric equivalent) would be extremely useful in determining area-capacity storage data, precise shoreline location, and the extent of the foreshore which would be affected by standing trees. This type of map embodies contours superimposed on photographic imagery and is especially applicable to shoreline planning and the assessment and planning of vegetation clearing.

In areas of steep shorelines, accurate contours are less important because the foreshore is limited. The effect of contour errors on area-capacity determination and location of the shoreline is diminished. Conversely, in areas where the shoreline gradient is slight the foreshore area can be very extensive and contour errors can result in an erroneous definition of the proposed shoreline by several thousands of feet.

Tributary and rainwater characteristics. Data from at least one year of monitoring are required for the following parameters: dissolved oxygen, suspended solids (including organic matter), dissolved solids (N, P, K, Ca, Mg, Fe, Si), nitrogen-phosphorus ratio, pH, temperature, and $CaCO_3$. Special attention should be given to water-quality analyses during peak runoff following intense downpours. Interpretations of climatic influences should be made on variations in water quality and on nutrient inputs from tributary waters and rainwater. Data collection should be integral to a long-term monitoring system of water characteristics.

Aquatic biota. In order to permit various interpretations, an inventory is needed of phytoplankton, zooplankton, other invertebrates including aquatic insects, and vertebrates in the river and upstream. For important disease vectors, studies are required of life cycles, habitat requirements for reproduction and growth, the ecology of parasite transmission, natural enemies, and other biological controls. The probable appearance of suitable habitats for disease vectors in the proposed reservoir should be determined, and zones of likely occurrence or concentrations should be identified. A detailed inventory of aquatic macrophytes and their ecology should be conducted for those species forming a suitable habitat for vectors to flourish.

For fish, life histories that include breeding and nutrition requirements are needed of major species that might adapt to the lacustrine environment. Exploratory fish catches in different parts of the basin and in different habitat conditions may be useful. Those fish species that are opportunist feeders and that breed all year or in the dry season (i.e., not dependent upon floods) should be considered as a first possibility for lake colonization. Their possible relative rarity in the river system (e.g., *Tilapia* and *Pellonula* in the Volta system) is not necessarily indicative of their colonization potential. River fishes that graze on periphyton attached to rocks and weeds in the river may adapt to periphyton that develop on standing vegetation in the reservoir (e.g., *Labeo* and *Leptotilapia* in the northern part of Volta Lake).

River fisheries. Surveys of existing river fishing should be made. Estimates of present approximate catch, fishing effort, and catch levels should be developed to indicate not only what might be lost at impoundment but also to provide data on the fishing methods practiced. This knowledge will be important in assessing the needs for assistance in developing new methods for the man-made lake.

1) *What is likely to be the productivity status of the reservoir during the filling and after stabilization? What is the likely mineral cycle?*

Data needed to assess short-term productivity (during early filling) as well as long-term productivity will be the same; water quality, inflow and outflow volume, and species composition of aquatic flora and fauna in the lake.

The nutrient status of lake tributary water will indicate, in general, the likely productivity status of the future lake. If inflowing waters are relatively low in nutrients, it would be especially desirable to obtain data which would make possible the prediction of the fish biomass peak which follows the initial flush of nutrients from drowned biota. This prediction can best be accomplished by closely monitoring fish populations after dam closure by means of experimental fishing. Catches should be timed to make possible the detection of trends so that fishing methods and fishing effort can respond to the increase in fish populations.

General productivity in terms of total biomass in the lake can be roughly predicted on the basis of Ryder's morphoedaphic index (Ryder, 1965). Initially developed for temperate-zone lakes, this index has been applied to tropical man-made lakes with good results. It is calculated as the ratio of total dissolved solids in mg/l to the mean lake depth in meters and is converted to kilograms per hectare. The mean lake depth can be known before impoundment, but projections of total dissolved solids would be subject to a considerable range of error because of the influence of (1) the initial flush of nutrients stored in drowned biota and (2) the eventual entrapment of nutrients in sediment and in biota such as water weeds. Neither factor can be predicted with confidence, but they should be assessed if they are suspected to be important in the mineral cycle of the lake. The combined viewpoint of a plant ecologist and limnologist--both with experience in the region--should be used to make the best assessment from existing data.

2) *What important fish species are likely to become established and/or abundant in the future reservoir? What fishing methods will be most efficient for food fish? Will reservoir vegetation, if left standing, interfere with these fishing methods?*

3) *Are there water weeds in the river systems that are likely to flourish in the new lake? If so, what species, and what are their habitat requirements? Are these weeds likely to harbor disease vectors or obstruct navigation and fisheries? If so, to what degree? Are problem weeds likely to persist?*

4) *What human and animal disease vectors are likely to be associated with the future man-made lake? What are their habitat requirements, and what are the control possibilities? Will control necessitate lowering reservoir levels to strand vectors such as intermediate snail hosts of schistosomiasis? Will this conflict with hydropower production and maintenance of adequate storage levels?*

Data from the inventory and river flora and fauna should be analyzed and interpreted in terms of probable species adaptations to the lacustrine conditions of the particular reservoir site. Special attention should focus on species which exploit the high productivity of seasonally flooded backwater areas and which are likely to adapt to the productivity status of the proposed reservoir, provided habitat requirements are met (e.g., for fish, dissolved oxygen, breeding and spawning habitat; for rooted macrophytes, nature and extent of suitable substrate). Estimates of total sustainable production in terms of biomass should be made, and probable food webs of important species should be projected. Estimates of abundance and probable production of food fish should be made.

While food webs and their species composition and abundance will be slightly different for each reservoir, research on existing tropical lakes and reservoirs (especially in Africa and parts of Asia) have made possible a fair understanding of what may evolve, especially at the lower steps of the food chain and, of course, at the level of primary production. The potential for water-weed problems (e.g., primary production level) can be predicted with some degree of confidence from the presence or absence of weeds in the river system. Potential biomass of fish that are consumers of phytoplankton can be predicted to some extent, but with less confidence because species adaptability to the lacustrine habitat will be a complicating factor. At higher trophic levels, the question of adaptability also is raised, and it is further complicated by competition and other factors which will determine the way food webs evolve and achieve recognizable patterns (e.g., relative stability). Experienced fisheries biologists and limnologists will be needed to make these kinds of assessments.

Once the dam is closed, assessment studies of fish stock and studies of fish feeding should be initiated. Initial stock assessment can be done by examining fish catches and by experimental catches. Once the lake begins to stabilize (after the first year or two in tropical systems), experimental fishing can be expanded to obtain more statistically representative data. If it becomes apparent that stocks are increasing but are unharvested or underfished, appropriate fishing methods may be investigated.

To assess the waterborne disease potential, inventory data on both disease vectors and water weeds or other substrate should be related to likely conditions in the reservoir. Possible engineering solutions for vectors and water weeds--such as spilling of lake water to strand them--should be related to the project design and downstream effects. Needed programs should be identified and their costs estimated.

5) *What are the likely effects of various alternatives with respect to the vegetative cover in the reservoir site--complete or partial removal, felling in place, leave standing--on fisheries productivity, water weeds,*

and navigation? Have navigation channel needs been anticipated and assessed in terms of what to do with the vegetative cover?

Aerial and ground surveys of standing vegetation at the reservoir site should be compared to probable fishing and navigation patterns and to resettlement community and port design. Shore areas that need clearing should be identified and the cost of clearing should be estimated. The relative vulnerability to decomposition of tree trunks and large branches should be assessed. The occurrence, at the site, of hardwoods with relatively high resistance to biological attack (e.g., teak, *Tectona grandis*, or mahogany, *Swietenia* spp.) should be surveyed and related to fishing and navigational obstacles that could be posed by their presence. Data and interpretations on fish production and probable fishing methods should be related to the existing vegetation in order to assess the needs for felling or removing trees. The desirability of leaving brush or trees standing in order to provide substrate or periphyton and/or refugia for fish should be assessed. Cost estimates of various alternatives for dealing with the vegetation of the site should consider the possibilities of labor-intensive methods suitable for employment of people that would have to be resettled.

6) *Will human habits or practices increase the risk of human exposure to disease in the reservoir area (e.g., elimination of body wastes in lake water, bathing, diving to set fish traps, etc.)? What measures are being considered or would be needed to correct such practices?*

Interpretations of fisheries and disease-vector problems should be related to human exposure to disease. Human-exposure factors to be considered should include: the likelihood of spontaneous settlement of fishing communities along the lake shore; traditional fishing methods; likely movements of people on the proposed lake; probability of parasite introductions for suitable vectors by persons from outside the region; customary personal hygiene; and the disposal of human wastes. Public health needs should be outlined, costed, and related to resettlement strategies and design of sites and services.

III. ENVIRONMENTAL AND ECOLOGICAL IMPACTS OF A TROPICAL RESERVOIR: SUMMARY OF A CASE STUDY OF VOLTA LAKE

A. INTRODUCTION

A review of various environmental impacts and changes brought about by the Volta Dam and the creation of Volta Lake was carried out in 1973 by eight scientists for the Smithsonian Institution (see Preface) in collaboration with the Volta River Authority. A study agenda was followed which complemented on-going fisheries, water-weed, and hydrobiological studies that were being carried out under the Volta Lake Research Program, sponsored in part by the UNDP. That research program, which began in 1967, was preceded by postimpoundment hydrobiological surveys and preimpoundment archeological and river surveys undertaken by the University of Ghana's Volta Basin Research Project. The Institute of Aquatic Biology of the Council of Industrial and Scientific Research participated in these research and survey programs.

The case study was carried out over a six-month period by means of literature reviews, interviews, and brief periods of field observations not exceeding three weeks. Lake geology and groundwater were reviewed by Dr. Harold E. Thomas, with particular reference to changes in groundwater movement of potential consequence to reservoir storage. Dr. Daniel A. Livingstone evaluated the lake's mineral cycle and Dr. A. M. Beeton reviewed plankton production. These aspects were fundamental to the studies of aquatic weeds and of fish nutrition and production respectively carried out by Dr. John J. Gaudet and Dr. Julian D. Reynolds. The lake's topography and the possibilities of obtaining better bathymetric information were reviewed by Mr. William S. Robinson. Dr. John Boland studied the water supply and sewage aspects and Dr. Lloyd Knutson reviewed the possibilities for biological control of various disease vectors associated with the lake.

Volta Lake began to fill in May 1963 and had reached projected capacity by 1973, thus becoming the largest man-made lake in the world--over 8,730 sq km in extent and 165 km^3 in volume at high water. The lake is dendritic in shape (Figure 4) with an extensive shoreline (6,400 km). Due to shallow foreshore gradients, 500 to 1000 sq km of surface are alternately flooded and exposed. This drawdown zone is of great importance for fisheries productivity. Also associated with the drawdown, however, are water weeds and related schistosomiasis problems.

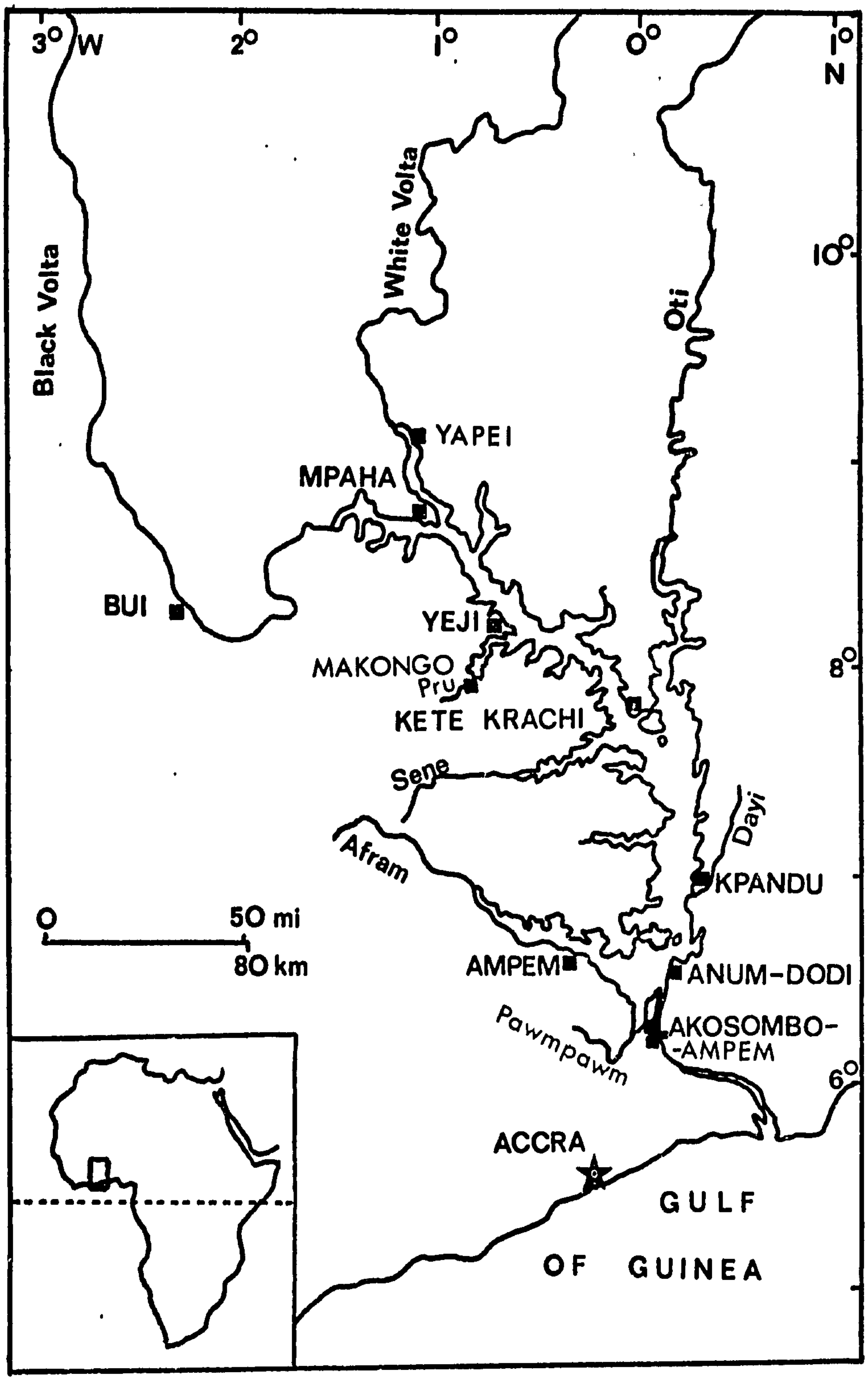

Figure 4. Index map of Volta Lake and environs.

More than 80,000 people had to be relocated, with 69,000 being moved to 52 resettlement villages established by the Volta River Authority. In addition to the population of the resettlement villages, some 60,000 persons live along the shores in spontaneously constructed fishing villages. A portion of these fishing-village dwellers are persons who have left the resettlement villages. Many migrated from below the dam. They exploit the lake's fisheries by using craft and techniques that originally were adapted to river fishing but that are slowly evolving towards lake fishing.

The dam's hydropower plant has a generating capacity of 769 megawatts, about half of which powers the Valco aluminum refinery in Tema on the coast. The remainder is transmitted to Accra, and a 200,000-hectare irrigation scheme planned for the Accra plains would be supplied by water from the river or the lake.

The dam was financed through a complex scheme whose participants included the International Bank for Reconstruction and Development, the governments of England and the United States, Kaiser Aluminium and Chemical Corporation, and Reynolds Metals Company. The dam and power plant cost $196 million and the Valco aluminium smelter $128 million. The smelter investment was backed by a 30-year power contract with the Volta River Authority (VRA). That Authority was established to construct and operate the dam and power plant. Also, the VRA carried out resettlement following dam closure and has been a major participant in the Volta Lake Research Project.

The problems of resettlement, water weeds, and various diseases in the impoundment area were anticipated before dam construction and led to preimpoundment and postimpoundment surveys and research. However, no fish surveys of the Volta River were undertaken prior to impoundment. With the exception of a number of independent studies, the downstream impacts of the dam have not been well studied, although there was early recognition of some of the possible impacts. Projections of potential annual fish production made prior to impoundment were low at 18,000 m.t. compared to the sustainable yield of 40,000 m.t. per year, which is now judged possible, and to the peak production of 60,000 m.t. harvested in 1969. This unplanned benefit took on special significance because of the difficulties which emerged in the resettlement program. That program was premised on mechanized agriculture, not fishing, even though many of the relocated peoples had engaged in river fishing. The case study did not, however, examine the resettlement question.

The major gaps in knowledge (in addition to the lack of downstream studies) are in the areas of mineral cycling, as it relates to lake productivity, and of sedimentation measurements. There also is a need for biological-control research on water weeds and disease vectors, which is of considerable importance given the failures to date to control the *Bulinus* intermediate snail host of urinary schistosomiasis and its preferred habitat, the beds of *Ceratophyllum*. Also, information on the lake's bathymetry and morphology--especially in the live storage zone--is not accurate enough for multiple-purpose planning of the lake's water resource. This will become increasingly serious as additional demands are made on the lake's water supply.

These information gaps exacerbate the management aspects of the drawdown zone. Here there is greatest human exposure to the water, hence to infestation by schistosomiasis. Lake water, important for domestic supplies, is drawn regularly by children. Fish harvests are high along the shore because of its high productivity. A preferred method for catching *Tilapia* inshore is by traps, which are set by diving and thereby adding to the exposure risk. The water-weed habitat for the snail has proven difficult to eliminate, and the use of some of the more effective herbicides has the undesirable side effect of contaminating drawdown soil and inhibiting growth of susceptible crops such as tomatoes and tobacco. On the other hand, mechanical clearing is quite labor-intensive and must be well timed and continuous to be successful. The drawdown area can be viewed as an ecological interface, which is both highly productive and beset with problems because of that productivity. Problems in the drawdown zone similar to those experienced on Volta Lake can be expected in future tropical reservoirs.

B. SUMMARY OF FINDINGS

Lake Geology

Existing published and unpublished data were reviewed, but original field survey work on the geology of the lake 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 sandstone beds form escarpments in excess of 300 meters above sea level in extensive areas along the northern and western rims of the basin and a distinctly 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 precambrian granites, metamorphosed sediments, and lavas, including the Togo quartzites that outcrop at the Akosombo Dam. Mineral resources flooded by the dam were 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 amount is reduced by about 25 x 10^9 tons during low water. The seismic effect of the added weight is not known. In Ghana the zone of major seismicity is in a triangle extending southeastward from the Togo quartzite. Three earthquakes of intensity 5 on the Modified Mercalli scale have occurred since the filling of the lake began in 1964. Two of these earthquakes had epicenters offshore from Accra, while the epicenter of the third was 40 miles south of Akosombo, near Koforidua. No special measurements have been undertaken to determine the seismic effects associated with the reservoir's 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 considered 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 buildup by coarse sediments in the mouths of major tributaries.

Groundwater Geology and Related Hydrology

Because of the absence of preimpoundment 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 obviously is influenced by seasonal fluctuations in reservoir level, but this is judged to be significant only to crop production. Seismic subbottom 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's 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 runoff. 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 runoff in the basin varies considerably from year to year. In 28 years the recorded runoff 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 recentness of continuing hydrologic observations (since 1959) in the Volta Basin 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 winds may be a conseq[illegible]f nighttime convective air currents over the water surfa[illegible]ich draw cooler air descending from the mountain range [illegible]ith of that shore. But they could also be a consequence o[illegible]e 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. In the Accra Plains eight research wells have averaged 600 to 1,500 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 recharge rates due to the impermeability of the subsoil above aquifers. Wells are not presently monitored, however.

Lake Topographic Survey

A fathometric survey trial with an electronic depth recorder was carried out to evaluate the adequacy of existing topographic information on the reservoir. Also, survey needs for sedimentation were reviewed and recommendations were formulated for surveys and mapping that would be desirable for the purposes of more accurate determination of area-capacity, navigation, sedimentation buildup, 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 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. Submerged vegetation was recorded on the charts but it did not confuse the registration of the bottom (Figure 5).

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, but more accurate area-capacity curves will be needed--particularly

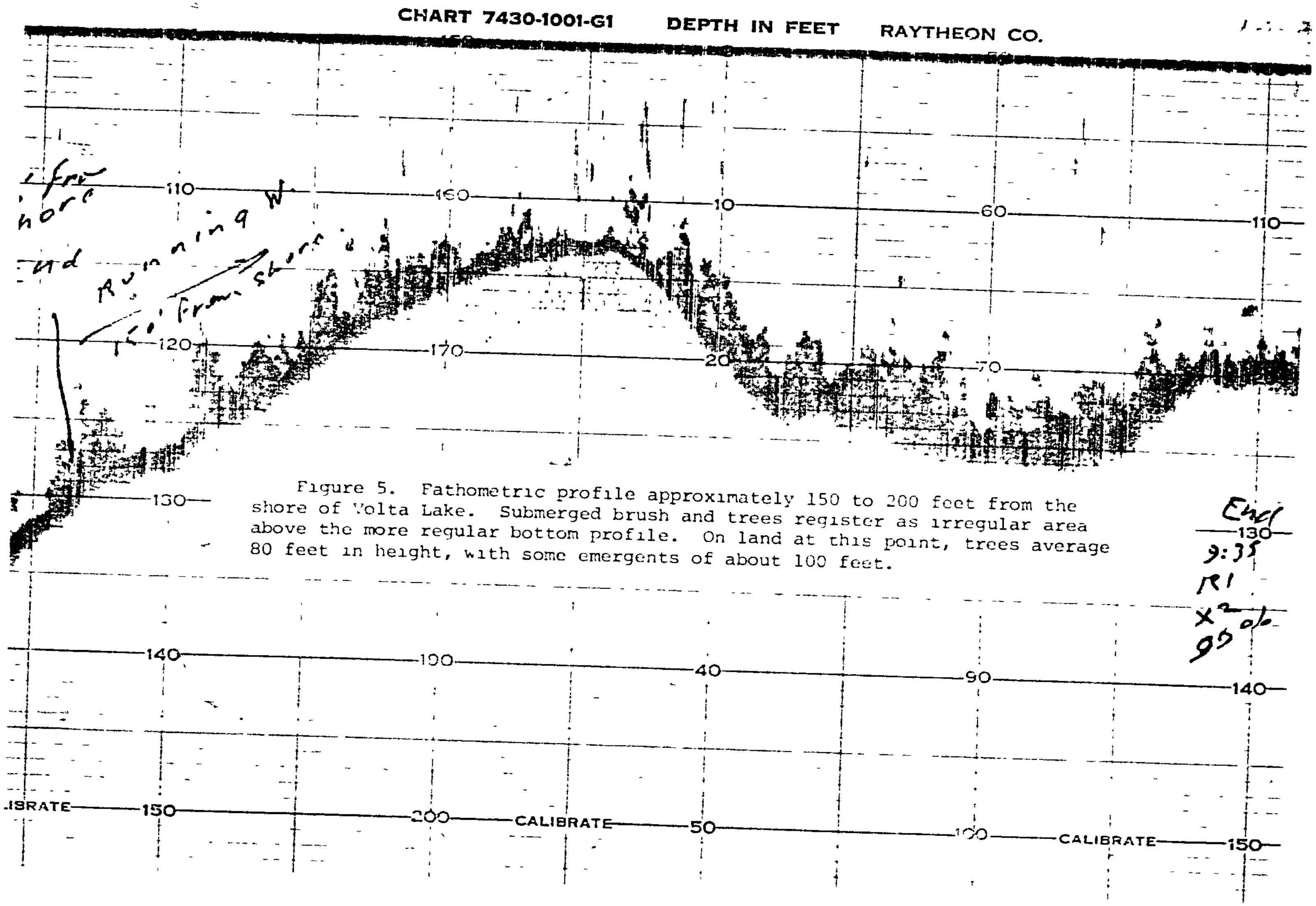

Figure 5. Fathometric profile approximately 150 to 200 feet from the shore of Volta Lake. Submerged brush and trees register as irregular area above the more regular bottom profile. On land at this point, trees average 80 feet in height, with some emergents of about 100 feet.

at the 248 to 276 foot, "live storage" level--if additional uses are to be made of the water. Also inherent inaccuracies make the existing topographic maps 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, the drawdown 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 were suggested. Both would utilize existing 1:50,000 aerial photomosaics of the lake that were constructed in 1971 for the Volta Lake Research Project. The first alternative would be to take, at a relatively high altitude, black-and-white aerial photographs (panchromatic or infrared) 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 five-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 225-foot level, the second alternative would be a bathymetric survey to define bottom contours at five-foot intervals down to 248 feet. New mapping is not needed for steeper shores because 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. Presently, drowned emergent trees serve as channel markers, but the decay of these and the buildup of sediments at the mouths of tributaries eventually will make surveys necessary. Bathymetric surveys should be undertaken of all proposed navigation channels. Tributary delta buildup should not significantly affect the reservoir storage capacity; however, 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. It is recommended that relatively inexpensive tiltmeters be installed at the lower levels of the power structure and spillways to supplement existing seismometers.

Mineral Cycling

On the basis of existing data, several of the Smithsonian consultants reviewed changes in mineral cycling in the reservoir area and below the dam. They agreed with most Ghanaian scientists that 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. The absence of chemistry measurements of preimpoundment water below the dam prohibits use of subsequent water-chemistry data for deducing the downstream changes in the river's mineral status.

A number of questions must be answered before the lake's mineral cycle, and therefore its productivity, can be understood: Are major nutrients (and accessory growth substances) in chemical forms which can be used by algae? To what extent 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 runoff, and precipitation? To what extent are nutrients lost to sediments and/or returned from sediments? The last question is related to the question of fertilization of the lake, and it is 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 the 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 5 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 waves 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. Prior to impoundment, the enrichment of estuaries and floodplains 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 runoff during the rainy season prior to impoundment would have tended to prevent up-welling.

Aquatic vegetation was judged 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 that 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's edge. Estimates were made of the amounts of minerals trapped in three dominant species--*Ceratophyllum demersum, Pistia stratiotes,* and *Polygonum* sp. Out of an estimated 15,569 m.t. trapped, 31 percent would be nitrogen, 30 percent potassium, 21 percent iron, and 8 percent phosphorus. The total represents more than a third as much as the 41,000 m.t. of minerals that are estimated 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 levels at Ajena in 1970-1972 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 was implicit in the analyses of fish nutrition. The large store of nutrients in 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 the drawdown zone and adjacent portions of the littoral that the major catch of *Tilapia* spp. is made (Table 5).

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. Abundance appears to be 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.

In Volta Lake more is known about phytoplankton 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.

Table 5 Comparison of fish in different littoral habitats

Habitat	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

Source: Loiselle, 1972.

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 9 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 4 to 15 percent, and crustaceans 6 percent. Little information is available on planktonic crustacea as food for larval and juvenile fish, although zooplankton has been found to comprise 1 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 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 also were 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. This, however, did not become a problem of the same magnitude as has occurred on Lake Kariba, except in the Afram arm to the southwest.

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 a decrease in population. This is explained by the reliance of *Pistia* on dissolved nutrients, which initially were 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*. Nevertheless, *Pistia* is well established in the lake, especially in protected embayments.

d. The appearance of *Vossia* spp. as the dominant emergent plant in the drawdown area. Reasons for this are the plant's 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*), all of which gives *Vossia* an advantage over its competitor, *Polygonum*. *Vossia* also is relatively resistant to herbicides, and it 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 lakeshore drawdown zone.

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

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* (Table 6). 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.

Table No. 6 Distribution of *Bulinus* snails on substrates sampled over 24 months on Volta Lake

. Substrate	No. of snails	Percent 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

Source: Odei, 1973.

The main benefits of the weeds are their contribution to fish production as food, substrate for periphyton, and as spawning and breeding habitat. *Vossia* beds are a productive fish habitat, having 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.

Weed control and clearing experiments carried out at Ampem by Pierce (1971) and Opoku (1971, 1973) were reviewed. 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 the plants were young; however, there were several complications. 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, was only temporary since *Vossia* 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 the

Plate 6. Maintenance of weed-free shore by hand-clearing ahead of rising lake water.

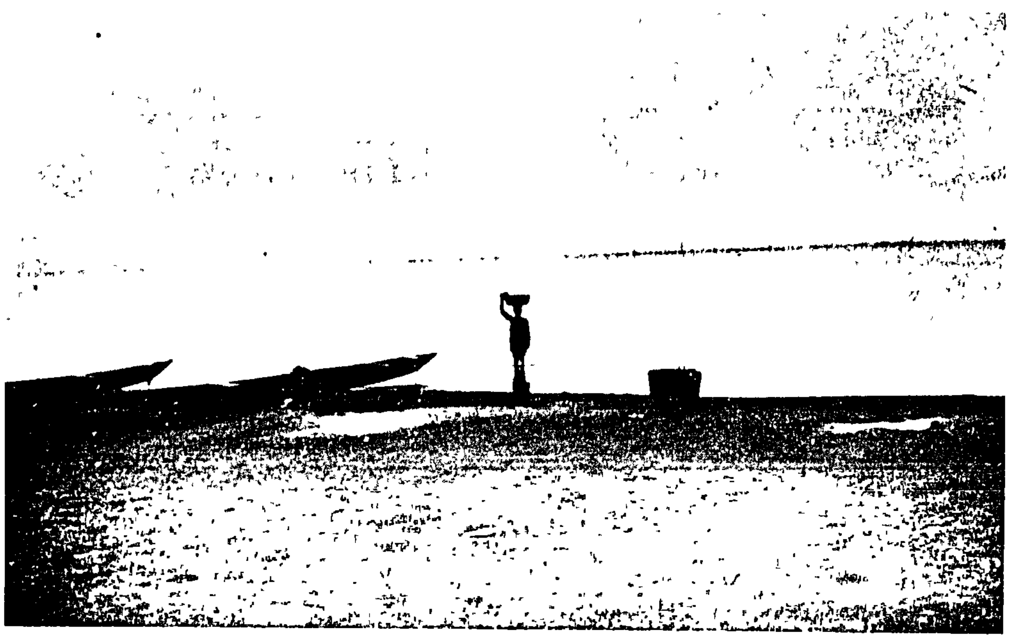

Plate 7. Drawing lake water increases risk of schistosomiasis infestation. Control of the habitat of the snail's intermediate host weed can, however, reduce the risk.

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 inhibit crop growth.

This work and later trials have shown that the only weed-clearing technique on Volta Lake that has worked well consists of burning, cutting, and hoeing. This proved to be fairly labor-intensive: 27 man-days were needed for initial clearing and an average of 22 man-days/ha/year was required to maintain a weed-free plot. Maintenance required cutting the vegetation to soil level just ahead of the rising water. Conflicts were posed since that time of 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 that are cheaper and ecologically safer should be undertaken.

The only important weed known to have natural control is *Polygonum*, which is attacked by the burrowing mayfly. *Polygonum* probably will 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 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 *Chrysicthys* and a permanent decline of most mormyrid species. The mormyrids apparently have been limited by the lower dissolved-oxygen level in the lake's water, especially just after closing. Although now at about 90 to 100 percent saturation that characterized the river. Disappearance of the mormyrids' rocky, riverine breeding habitat also has 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 insectivorous families, which are facultative feeders and 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 lake 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--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 gradients apparently have resulted in considerable benthic production, and the mudsucking *Labeo* is an important commercial fish there. However, in terms of weight, the pelagic *Pellonula* spp., which feed on aquatic insects living in the periphyton and on zooplankton, are the dominant fishes on the lake. Although not commercially fished, their predator, *Lates*, is now the second most important fish caught in terms of weight. The 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. Following the decline of the nutrient sources in the drowned vegetation and the stabilization of the lake's ecosystem at an oligotrophic level, the approximately 80,000 ha surface of the drawdown areas has become very important to the lake's fish productivity. 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. *Tilapia* spp. comprise about half the current catch and 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 and they provide substrate for periphyton, as well as refugium for juveniles (mainly in the northern lake, in Reynold's opinion). *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, *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 harvest of the lake's fisheries greatly exceeded the 18,000 t/year estimates made prior to impoundment, especially

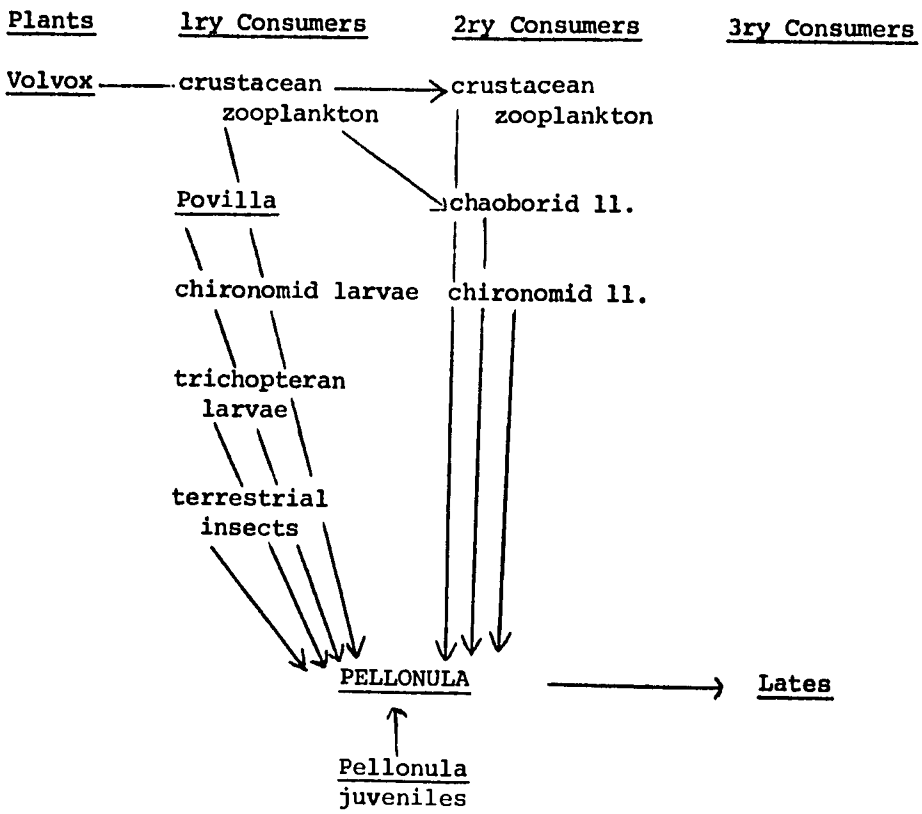

Figure 6. Pellonula food web.

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 and 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 g ater transparency and poorer catches from multifilament nets. In 1971, *Tilapia* constituted 50 percent of the catch, while other important genera were *Lates, Alestes,* and *Labeo*.

Presently, there are no total indicators of fish production from the whole lake and there is no feasible method for assessing the absolute abundance or production of the biomass of pelagic fish.

Tentative projections of trends in species abundance suggested 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 (*Chysichthys* spp.) in the south, and the dominance in open waters of the south lake by *Pellonula* and its predator *Lates* (Figure 2).

The potential productivity of the lake was assessed with Ryder's morphoedaphic index of productivity, based upon dissolved solids and mean depth. This index indicated an annual sustainable yield of 40,000 mt, or 35-40 kg/ha. The validity of this calculation is corroborated to some extent by results of a similar estimate made of productivity in Lake Kainji. There, results from using Ryder's index corresponded closely with the lower range of productivity computed by different methods. On Volta Lake, the yearly production potential as indicated by Ryder's morphoedaphic 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 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 was judged worthwhile to investigate the potential of converting shallows to fish ponds and to experiment with bundles of brush or reeds as substrate and refugia.

Water Supply and Sewage

Volta Lake can be described as a single environmental resource capable of providing a number of resource services; for example, hydropower, fisheries, water for irrigation and industry, and drinking water. 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. An optimal pattern of use would guarantee present and future combinations of various uses that are more satisfactory than alternate patterns. This optimal pattern of water resource management requires a statement of the societal goals for managing the resources that must take into account desired benefits as well as constraints on the attainment of such benefits. A formal articulation of the optimization or maximization problem will permit an analysis of proposed uses that would incorporate 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 (generate electricity to process bauxite), then a multiple-purpose focus (Halcrow and Partners, 1951 report), and a return to the single-purpose hydropower orientation (Kaiser Company, 1959 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. These can be termed water-supply services.

Water supply can be obtained from withdrawals 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 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 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, 4.5 liters would have to be released from the dam for every 3.8 liters 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 existed, 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 water supply, and for many it can be assumed that water is carried from the lake. This undoubtedly was 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 has experienced logistical problems in getting to the villages in order to maintain pumps. In addition to the hazard of schistosomiasis exposure, 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's 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, and 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 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 production of energy. The second alternative would be followed if the analysis showed that the net social benefit from the water use would compensate 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 Volta Lake to study the future demands for its resource services except in a superficial way. But significant withdrawals of water for irrigation purposes would surely compete with power-generation needs, and a multipurpose 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 Volta Lake. As opposed to irrigation demand, however, demands for drinking and industrial water do not have pronounced seasonal peaks. Accra and Tema could be supplied by river water pumped from points below the dam, and 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 multipurpose 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 not current problems. Use of certain persistent insecticides and herbicides in the drawdown-zone agriculture could, however, cause serious damage to sensitive fish and other aquatic life important to fisheries. In a hypothetical example, industrial wastewater pollution is tolerated at the sacrifice of reduced

fish catch. In this case, 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 independently of its tributary streams and the river below the dam. The formulation of a comprehensive river basin plan was recommended.

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 *(Coelomyces)* 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, hontonectids, belstomastids, beetle larvae, and undoubtedly some native fish. These organisms have not yet been researched for their biological control values, however.

The dam flooded large areas of the forest habitat of the tsetse fly, vector of sleeping sickness. While prospects for biological control are very limited due to lack of knowledge of natural enemies, cleaning 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, and exposure to infestation is high, especially for fishermen who dive to set nets and for people who draw water from the lake; the latter are commonly children.

Biological control could focus on the habitat of the vector snail, the snails, the cercariae, the miracidia, and intramolluscan stages. No effective control has been devised for the submerged *Ceratophyllum* weed, in which the *Bulinus* snail vector is found in most abundance. *Ceratophyllum* 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 waterfowl. (It has been observed that there are low populations of snails in villages on the lake with domestic ducks.) Both these predators deserve serious consideration as control agents. To a slight extent, *Bulinus* snails also are attacked by young *Lates, Alestes baremose, Physailia,* and *Synodontis* spp.

Larvae of the Scyiomyzidae flies are known to prey upon snails, and 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. However, 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 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 nondisease-producing 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, nondisease-producing trematodes may be used to shorten the life of the snail or to reduce its fecundity by parasitic castration.

Surveys and basic taxonomic studies are fundamental needs in Ghana for advancing the possibilities of biological control on Volta Lake. Knowledge must also be developed on the relationships between the candidate biological control agent(s), the target organism, and other members of the ecosystem. An additional consideration concerns environmental stability. Biological methods of control in man-made lakes can best be developed in a relatively stable physical environment. This is particularly important with respect to the role of aquatic plants in the ecology of disease. Relative stability in aquatic plant succession has apparently occured on Volta Lake. Thus, biological control is now more feasible than in the earlier, unstable years, following closure of the Akosombo Dam.

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APPENDIX

WORLD BANK GUIDELINES FOR THE ASSESSMENT OF DAMS

The questions listed below are extracted from the publication *Environmental, Health, and Human Ecologic Considerations* (World Bank, 1973). According to the preface of this publication, the guidelines were designed to provide guidance to Bank staff in the detection, identification, and measurement of environmental and related human ecologic effects of development projects, in this case dams.

A. *Environmental/Resource Linkages*

Have alternatives to the dam been fully considered? Is the dam's presence and operation, including the impoundment, compatible with present or planned development of the region?

Is it a multipurpose dam? If not, could it be made multipurpose through modification?

Will important resources be lost or their use precluded because of the dam's presence or operation? Does the dam offer opportunities for enhancing the environment through planned modifications in design or operating regimes?

Will new settlements and/or cultivation of reservoir slopes cause erosion and premature silting up of the impoundment?

Will alteration of the water regime (e.g., seasonal flooding, etc.) have important environmental or human ecologic implications?

Will aquatic weeds and the introduction or exacerbation of diseases constitute formidable and costly problems?

What is the nature and magnitude of the human resettlement problems? Are there adequate resources to carry it out in a manner minimally disruptive of the well-being of the affected peoples?

Will new public health problems arise as a result of the project?

Will important historic, religious, archeological, or geological sites be inundated?

Will the operation of the dam affect the interests of nation(s) downstream and, if so, has the latter been consulted?

B. *Design and Construction*

Will the design allow for the movement of important migratory fish populations?

Will the dam construction activities be carried out in a manner that will minimize erosion and other damage to the environment?

Are road patterns, land excavations, fill sites, and refuse disposal activities consistent with good environmental protection practices?

Will land in construction areas be restored by filling, grading, reseeding and reforestation to prevent erosion and erase scars?

Will trees and vegetation be removed from the impoundment area to minimize the introduction of aquatic weeds and to improve the habitat for an exploitable fishery?

Will control of disease vectors be carried out during the construction period?

C. *Operations*

Can the operating regime be made to benefit fish and wildlife resources wherever possible?

How fast will siltation occur and how can it best be handled?

How will aquatic weeds be controlled?

Will there be undesirable interactions between the altered surface water patterns and underground aquifers and their recharge?

What physical and biological alterations can be expected to take place in downstream, estuarine, and ultimate discharge areas?

Can changes in water salinity be expected? How will this be handled?

Will new settlements and cultivated areas contribute sediment and pollutants, including fertilizer and pesticide runoff, to the impoundment? How will this be controlled?

Will land-use planning, zoning, and other measures be employed to protect the watershed area from practices and activities detrimental to the project?

Will important wildlife forms be salvaged and/or relocated?

D. *Socio-Cultural Factors*

What will be the human ecological consequences of changes in land-use and economic activities, population redistribution, influx of migrants, and changes in life styles and traditional living patterns?

Have resettlement plans had the benefit of social scientists and anthropologists? Are such plans in keeping with the sociocultural needs of the affected peoples? Will the new settlements have adequate provisions for sanitation, disease control, and health care services?

Will measures be taken to control squatting on riparian lands and undesirable crowding around the periphery?

Will religious and historic sites and artifacts important to local peoples be salvaged and preserved?

E. *Health Impacts*

What types of health problems will arise and how will they be controlled?

Will the work force, including families, be given a preemployment medical screening to prevent the introduction of new diseases? Will they receive periodic examinations to detect diseases and parasitism, and to receive clinical treatment? Will arrangements be made with local health authorities to control venereal disease and enforce environmental sanitation standards?

F. *Long-Term Considerations*

Will contingency resources be available to cope with unforeseen or unexpected environmental and health problems?

Will any provision be made for follow-up studies of the environmental and human ecologic consequen-es of the project?